

Modeling of overvoltages in gas insulated substations

Abstract. Gas Insulated Substations (GIS) are broadly used for transmission and distribution of electric power. Due to the interactions with a network and various environmental phenomena like lightning the GIS are subjected to the Very Fast Transients (VFT). Such VFT can be also created within GIS mainly by the disconnecter operations. Paper will present an approach towards modeling of transient phenomena in GIS. The simulation of transients in exemplary high voltage power supply substation will be shown.

Streszczenie. Stacje izolowane gazem SF₆ (GIS) są szeroko wykorzystywane w elektroenergetycznych systemach przesyłowych i dystrybucyjnych. W wyniku zjawisk przejściowych takich jak operacje łączeniowe oraz wyładowania atmosferyczne, stacje GIS narażone są na występowanie przepięć bardzo szybko zmiennych. Artykuł przedstawi zasady modelowania zjawisk przejściowych w stacjach GIS oraz przykładową analizę przepięć generowanych poprzez operowanie odłącznikiem. (Modelowanie przepięć w stacjach elektroenergetycznych izolowanych gazem SF₆)

Keywords: very fast transients overvoltages, switching, GIS substation, disconnecter, EMTP/ATP modeling, simulation

Słowa kluczowe: szybkozmiennne zjawiska przepięciowe, stacja izolowana gazem SF₆, odłącznik, EMTP/ATP modelowanie, symulacja

Introduction

The Very Fast Transients (VFT) in power systems cover a frequency range from 100 kHz up to hundreds of MHz [1, 2]. VFT are an effect of GIS disconnecter opening or closing, as well as other events such as operation of a circuit breakers or grounding switches. An electromagnetic wave is generated, which propagates along the busbars and substation apparatus. Due to the fact that it can be multiple times reflected at joints between substation equipment, its maximum overvoltage peak values can reach significant levels. Their magnitude is in the range of 1.5 to 2.0 p.u. of the line-to-neutral voltage crest, but they can also reach values as high as 2.5 p.u. to 3 p.u. in case of ultra high voltage systems. These values are generally below the Basic Insulation Level (BIL), but VFT can speed up insulations aging and degradation processes due to their frequent occurrences.

The fact of VFT occurrence in high voltage power systems forces to study them in an analytical manner. It is important to recognize its possible maximum overvoltage peak values in order to determine if those are below acceptable insulation levels.

This paper presents a state of the art modeling principles for this kind of phenomena. Also exemplary 380 kV GIS substation have been analyzed. Overvoltage waveforms during GIS disconnecter closing operation have been calculated along with their maximum peak values. All simulations have been performed using ATPDraw 5.6p6 software package.

VFT phenomenon description

During the closing or opening operation of the disconnecter in adjacent bay of GIS substation (Fig. 1) an electric arc occurs multiple times between the contacts. These so called re-strikes and pre-strikes are a result of the relatively slow speed of disconnecter contacts moving. Sparks occurrence result in generation of overvoltage wave, which propagates along the substations. Its propagation is characterized by multiple reflections at substation equipment joints, which leads to high overvoltage peak values. It also has to be pointed out, that after the disconnecter opening operation, the capacitive *trapped charge voltage* remains on the disconnecter load side. It is being discharged very slowly through the GIS spacers and other equipment. However, during reclosing of the disconnecter this voltage can have a significant influence on generated overvoltages. The typical value of trapped charge voltage can be expected in the range of 0.3 ÷ 0.6

p.u. Nonetheless, for Insulation Co-ordination studies it is always required to analyze the worst case working conditions for specific network. Thus, it should be assumed, that the trapped charge voltage is equal to -1 p.u. of nominal system voltage, whereas the cosine source side voltage is equal to +1 p.u. It also has to be assumed that the studied system is running at its highest power frequency nominal voltage. It results then in significant potential difference between contacts during the spark occurrence, which leads to generation of most severe overvoltages.

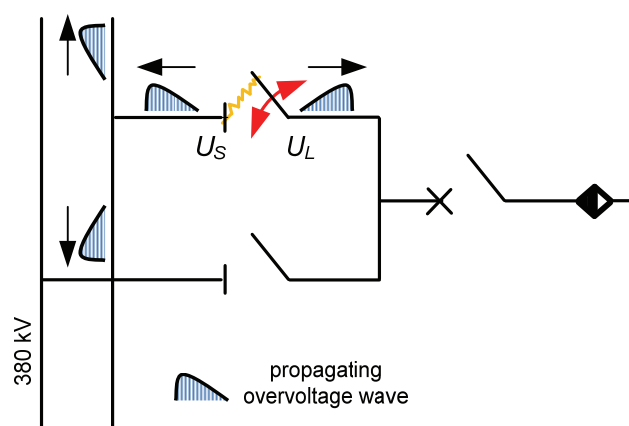


Fig. 1. VFT generation principle – disconnecter operating in the GIS substation: U_s – voltage at disconnecter source side, U_L – voltage at disconnecter load side

The switching and lightning overvoltages are a typical concern in high voltage power systems. Switching oscillations inside the GIS substations (Very Fast Transients) are characterized by a very high rise times, which results in the fact that in studied range of frequencies surge arresters are visible mainly as a phase to ground capacitance. Their nominal voltage-current nonlinear characteristics does not have significant influence on overvoltages suppression.

It has to be also said, that necessity of VFT analysis comes out of the fact, that the ratio of nominal system voltage and Switching Impulse Withstand Level SIWL is significantly less for ultra high voltage system than for medium voltage systems for instance. Comparison between nominal system ratings and acceptable switching overvoltage levels have been summarized in Table 1 [3, 5].

Table 1. Comparison of ratio between highest system voltages and their maximum switching impulse acceptable levels

highest voltage for equipment U_m [kV _{RMS}]	Switching Impulse Withstand Level S/WL [kV _{peak}]	ratio [p.u.]
24	145	7.40
52	250	5.89
123	550	5.48
145	650	5.49
245	950	4.75
420	1050	3.06
765	1550	2.48

As it is clearly visible in Table 1, the ratio between peak values of acceptable switching overvoltage and highest power frequency voltage for systems at 24 kV is equal to 7.40 p.u., whereas for ultra high voltages like for 765 kV is equal to 2.48 p.u. As it was stated before, overvoltages generated during Very Fast Transients phenomenon can reach peak values as high as 2.0 ÷ 3.0 p.u. Since this is very close to the maximum acceptable levels, the analysis of VFT overvoltages, quantity and frequency is very important.

Modeling principles for VFT

Very Fast Transients are characterized by rise times in the range of 4-100 ns. Thus, it has to be modeled as an appropriate distributed and lumped elements. The travelling nature of VFT forces one to use appropriate values of surge impedances with associated wave propagation speed and element length as well as phase-to-ground capacitances [4]. Detailed description have been presented in Table 2.

Table 2. GIS substation equipment modeling data for VFT

Component	Notes
busbar	$Z = 60 \Omega$, $l =$ „as per layout” $v = 290 \text{ m}/\mu\text{s}$
closed disconnector	$Z = 80 \Omega$
open disconnector	$C = 15 \text{ pF}$
open circuit breaker	$C = 700 \text{ pF}$
surge arrester	$C = 120 \text{ pF}$
voltage transformer	$C = 80 \text{ pF}$
SF6-air bushing	$C = 710 \text{ pF}$
HV cable	$Z = 20.6 \Omega$, $l =$ „as per layout” $v = 200 \text{ m}/\mu\text{s}$
overhead line	$R = 245 \Omega$

Special attention was paid to the power transformer modeling. It was represented by means of inductance, resistance and capacitance of HV bushings as well as capacitance of HV side windings. Parameters are evaluated from the frequency response analysis of the transformer. Typical values and used model have been presented in Figure 2.

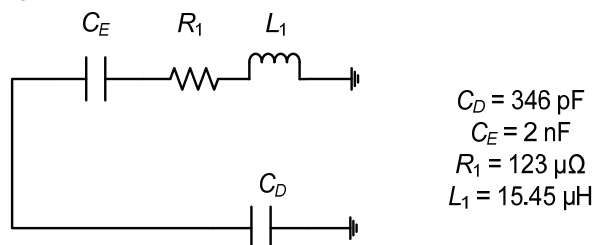


Fig. 2. High frequency model of the HV transformer side; C_D – HV side windings capacitance, C_E , R_1 , L_1 – capacitance, resistance and inductance of HV bushings

During the GIS disconnector closing operation, the voltage breakdown takes about 4 ns. The modeling of this event is made in EMTP/ATP with an exponentially

decreasing resistance r from very high value to zero with a time constant equal to $\tau = 0.6 \cdot 10^{-9} \text{ s}$, which results from disconnector capacitance and arc fixed resistance. The nonlinear arc resistance during closing event is implemented with use of MODELS language in EMTP/ATP according to formula (1):

$$(1) \quad r = 10^{12} e^{(-t/\tau)}$$

where: τ – time constant.

This non-linear resistance is in series with a fixed resistance of 0.5Ω , which represents the spark resistance after voltage breakdown.

For the worst case operating conditions, the damping of the Very Fast Transients, which occurs due to ohmic losses inside the GIS substation and mostly due to transition of the surge from inside to the outside earthing system at the bushing should not be considered.

Exemplary VFT analysis of 380 kV GIS substation

A typical 380 kV GIS substation has been considered for the VFT analysis. A single line diagram of part of the substation has been presented in Figure 3. It consists of 280 MVA power transformer that is energized through overhead transmission line interconnected to the substation with HV cable.

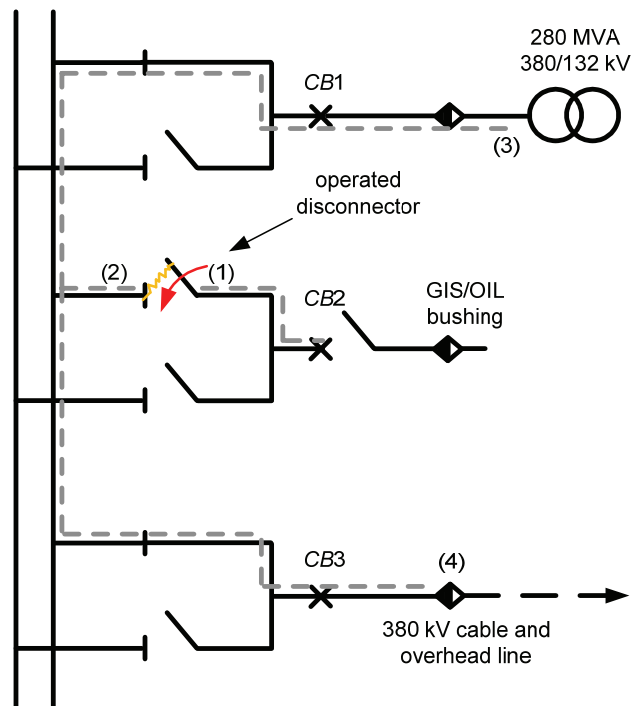


Fig. 3. 380 kV GIS substation – overall network diagram for VFT analysis

Singular switching operation (closing) of the disconnector have been simulated in EMTP/ATP software. As it is visible in Figure 3, circuit breaker CB2 is open during entire process of disconnector closing event, whereas circuit breakers CB1 and CB3 are closed and provide current path, which have been marked with dashed line. For the worst case operating conditions it has been assumed, that system is working at maximum allowed power frequency voltage (420 kV) and at the switching time instant source side voltage is at its maximum (+1 p.u.).

Overvoltage waveforms have been obtained at following locations (according to Fig. 3):

- disconnecter load side – position (1),
- disconnecter source side – position (2),
- transformer HV terminals – position (3),
- GIS-cable termination – position (4).

During the calculations, maximum overvoltage peak values have been obtained and compared to the Switching Impulse Withstand Voltage (SIWL) that is equal 1050 kV for 380 kV systems [5]. The nominal voltage in per units have been calculated according to formula (2):

$$(2) \quad 1 \text{ p.u.} = 420 \cdot \frac{\sqrt{2}}{\sqrt{3}} = 342.9 \text{ kV}$$

As it was discussed above, value of trapped charge voltage U_{TC} at disconnecter load side may have significant influence on generated overvoltages. Thus, two values of this voltage have been considered:

- case 1: $U_{TC} = -0.5 \text{ p.u.} = -171.45 \text{ kV}_{\text{peak}}$
- case 2: $U_{TC} = -1 \text{ p.u.} = -342.9 \text{ kV}_{\text{peak}}$

Simulation results

As it was described, the disconnecter closing event was modeled as an exponentially decreasing resistance. For this study, this operation was issued at the time instant of $t = 10 \mu\text{s}$. The nonlinear resistance decreases from very high value to 0.5Ω in about 4 ns (Fig 4). This behavior is independent from value of trapped charge voltage, thus it is the same for both cases with -1 p.u. and -0.5 p.u.

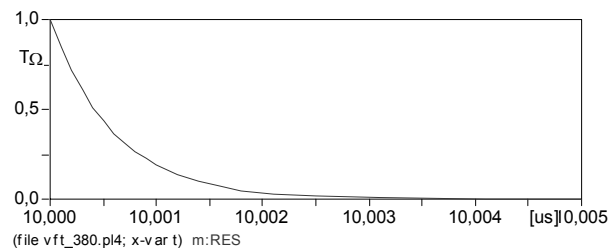


Fig. 4. Disconnecter nonlinear resistance during closing event

For each waveform, maximum overvoltage peak value have been obtained in kilovolts as well as in per units. Also percentage $\Delta\%$ difference between both scenarios have been calculated, according to formula (3):

$$(3) \quad \Delta\% = \frac{U_{C2} - U_{C1}}{U_{C2}} \cdot 100\%$$

where: U_{C1} , U_{C2} – calculated voltages at case 1 and case 2.

Summarized results for both analyzed scenarios have been presented in Table 3.

Table 3. Simulation results summary

Voltage measurement locations	Trapped charge voltage		Maximum overvoltage peak values	
	[p.u.]	[kV]	[p.u.]	[kV]
disconnecter load side (pos. 1)	-1	649	1.89	
	-0.5	572	1.67	
	$\Delta\%$		11.9	
disconnecter source side (pos. 2)	-1	655	1.91	
	-0.5	575	1.68	
	$\Delta\%$		12.2	
transformer HV terminals (pos. 3)	-1	551	1.61	
	-0.5	498	1.45	
	$\Delta\%$		9.6	
GIS-cable termination (pos. 4)	-1	464	1.35	
	-0.5	427	1.25	
	$\Delta\%$		8.0	

As it has been presented in Table 3, the highest overvoltage peak value occurred at the operated disconnecter terminals and is equal to 655 kV, which reaches level of almost 2 p.u. It can be also observed, that overvoltage magnitude decreased during propagation through the entire GIS substation. At the transformer terminals its peak value is equal to 551 kV, whereas at GIS extraction point it decreased to 464 kV. Once the overvoltage wave extracts out of the GIS, it is very quickly dumped on substation overhead connections and high voltage cables. Such behavior is visible for both analyzed cases, that is with -0.5 p.u. and -1 p.u. of trapped charge voltage at disconnecter load side. However, as it have been expected, calculated maximum overvoltage peak values are significantly lower with smaller trapped charge. Calculated voltage difference is in the range of 8.0 – 12.2 % and it is an obvious reason why during the typical insulation coordination studies all of the analyzes should be performed with -1 p.u. of assumed trapped charge voltage.

All reported values are well below maximum acceptable level of 1050 kV (Switching Impulse Withstand Level). During the insulation coordination processes it is necessary, to have all overvoltages below the safety margin of 80 % of SIWL, that is below 840 kV. As it is clearly visible in Table 3, all reported values are within acceptable limits.

Calculated overvoltage waveforms at specific locations of studied GIS substation have been illustrated in figures 5 to 8 for case 1 and in figures 9 to 12 for case 2.

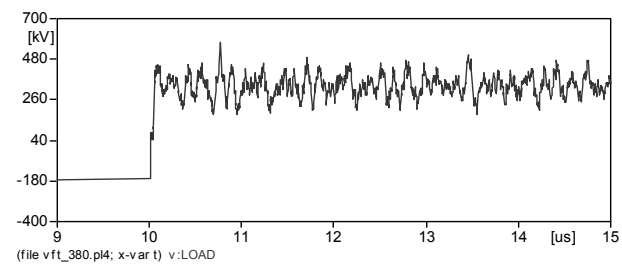


Fig. 5. VFT overvoltage waveforms, voltage at disconnecter load side, trapped charge voltage $U_{TC} = -0.5 \text{ p.u.}$

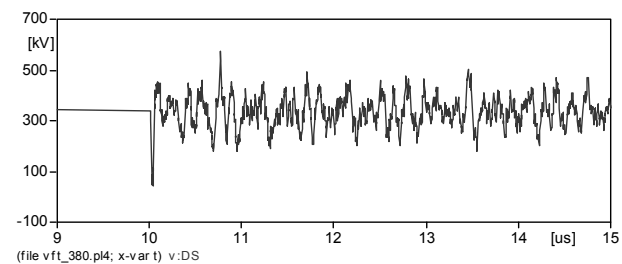


Fig. 6. VFT overvoltage waveforms, voltage at disconnecter source side, trapped charge voltage $U_{TC} = -0.5 \text{ p.u.}$

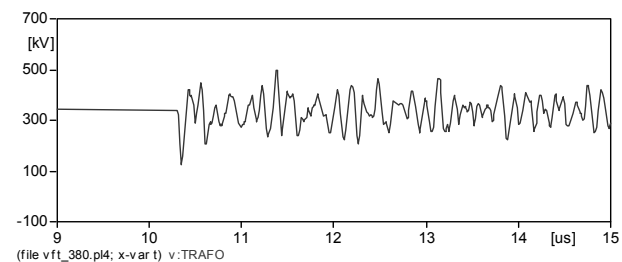
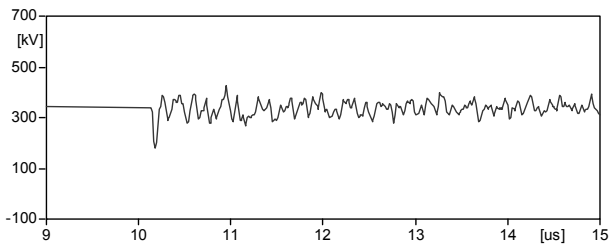
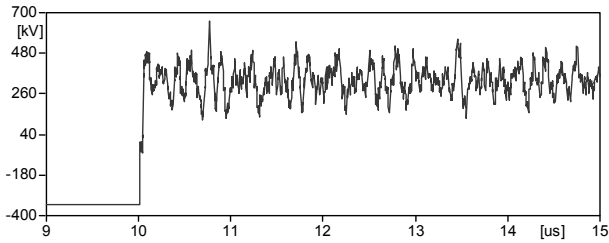


Fig. 7. VFT overvoltage waveforms, voltage at transformer HV terminals, trapped charge voltage $U_{TC} = -0.5 \text{ p.u.}$



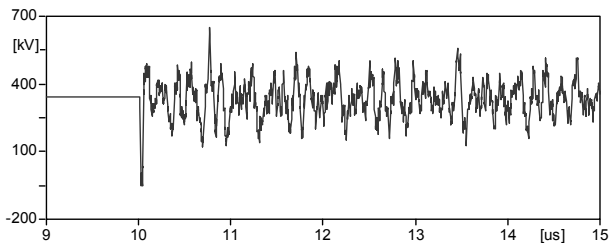
(file vft_380.pl4; x-var t) v:OUT

Fig. 8. VFT overvoltage waveforms, voltage at GIS-cable termination, trapped charge voltage $U_{TC} = -0.5$ p.u.



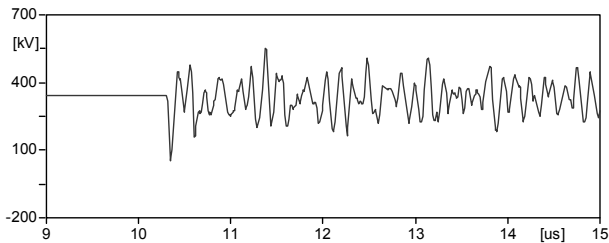
(file vft_380.pl4; x-var t) v:LOAD

Fig. 9. VFT overvoltage waveforms, voltage at disconnector load side, trapped charge voltage $U_{TC} = -1$ p.u.



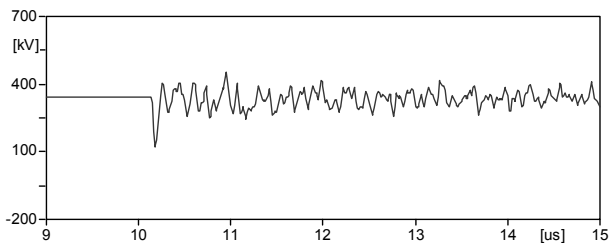
(file vft_380.pl4; x-var t) v:DS

Fig. 10. VFT overvoltage waveforms, voltage at disconnector source side, trapped charge voltage $U_{TC} = -1$ p.u.



(file vft_380.pl4; x-var t) v:TRAF0

Fig. 11. VFT overvoltage waveforms, voltage at transformer HV terminals, trapped charge voltage $U_{TC} = -1$ p.u.



(file vft_380.pl4; x-var t) v:OUT

Fig. 12. VFT overvoltage waveforms, voltage at GIS-cable termination, trapped charge voltage $U_{TC} = -1$ p.u.

As it is visible in all figures representing VFT overvoltage waveforms, disconnector have been closed at time instant of $t = 10 \mu\text{s}$. All overvoltage waveforms are characterized by multiple wave reflections resulting with very high frequencies in the range of 6 MHz to 10 MHz. In figures 5 and 9 it can be observed, that the disconnector load side is preloaded with trapped charge equal to -0.5 p.u. and -1 p.u. respectively. In figures 8 and 11, where voltage waveform at transformer HV terminals have been represented, one can observe, that the overvoltage wave is delayed in time of 300 ns from the assumed disconnector closing time instant of $10 \mu\text{s}$. This can be explained with the fact, that overvoltage wave propagates along entire GIS substation from the operated disconnector up to the transformer. Since this distance is equal to 86 m wave propagation speed can be easily calculated to $286 \text{ m}/\mu\text{s}$, which corresponds very well with assumed value of $290 \text{ m}/\mu\text{s}$. These values differ due to the presence of GIS equipment capacitances that smooth the overvoltage wave.

Conclusions

It has been presented, that with a detailed analysis and use of appropriate tools and modeling techniques, it is possible to evaluate maximum overvoltage peak values resulting from GIS disconnector closing operation. It is necessary to check if overvoltages are below maximum acceptable level of 80 % of Switching Impulse Withstand Level. It has been calculated, that maximum overvoltage peak value occurs at operated disconnector, however reported values are below the maximum acceptable levels. Based on studied cases with two different values of trapped charge it can be concluded, that during typical insulation coordination studies, for the worst case conditions it should be assumed, that trapped charge voltage at disconnector load side is equal to -1 p.u. As it has been presented, maximum overvoltage peak values can reach values up to 2.0 p.u. in this particular case. However, it has to be added, that phenomenon of Very Fast Transients propagation inside the GIS substations is very complex and complicated. Its analysis has to be performed with special attention to a specified substation layout, busbars lengths and cable or transformer connections and terminations.

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Authors: Tomasz Kuczek, MSc. Eng.,
 E-mail: tomasz.kuczeki@pl.abb.com, Marek Florkowski, D.Sc.
 Eng., E-mail: marek.florkowski@pl.abb.com, ABB Corporate
 Research Center, Starowiślna 13A., 31-038 Kraków, Poland