

ANALYSIS OF TRANSIENT OVERVOLTAGES IN HIGH VOLTAGE GAS INSULATED SUBSTATIONS

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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 equivalent parameters along with basic models considered in substation and high voltage network modeling will be described. The difference between low and high frequency modeling will be highlighted. The simulation of transients in exemplary high voltage substation will be shown.

Keywords: switching, transient overvoltage, GIS, disconnecter

1. INTRODUCTION

The Very Fast Transients (VFT) in power systems cover a frequency range from 100 kHz up to hundreds of MHz. 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 [1].

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.

2. TRANSIENT OVERVOLTAGES IN POWER SYSTEMS

Transient overvoltages in power systems can be generated during various types of phenomenon and are mainly characterized by their magnitude, rise time and frequency. Due to the fact, that any switching operation generates an overvoltage wave, it is important to take wave reflections into consideration during the modeling and analyses. It is well known, that propagating overvoltage wave behaves differently in parts of power systems with various surge impedances. It can be reflected, decreased or increased at any point of discontinuity. One of such scenarios can be an example of transmission line that is interconnected with substation through the cable (Fig. 1). Due to the fact, that surge impedance of overhead line is around 350 Ω , whereas for the cable 30 Ω , an overvoltage wave which passes through the cable to the substation is decreased.

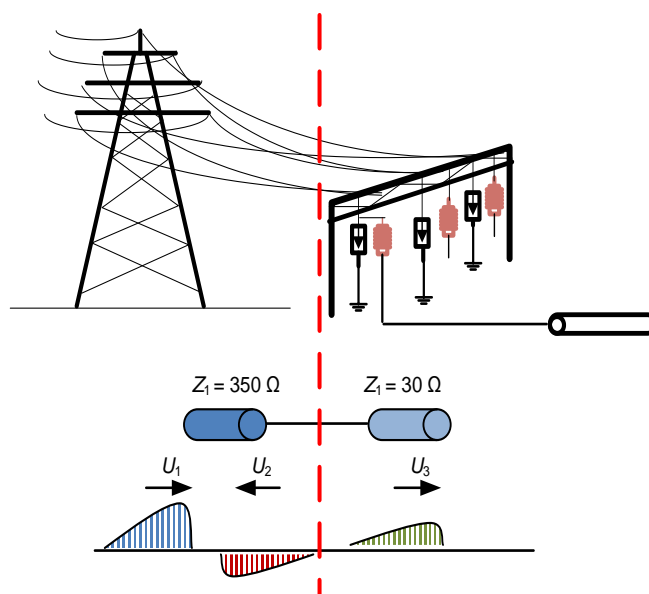


Fig. 1. Propagation of overvoltage wave in power systems; U_1 – propagating wave, U_2 – reflected wave, U_3 – passed through wave

First group of transients are the power frequency overvoltages caused by oscillations during phase to ground and phase to phase faults, as well as load rejection and ferroresonance effects. Their frequency is in the range of 10 to 500 Hz and magnitudes around 2.0 p.u.

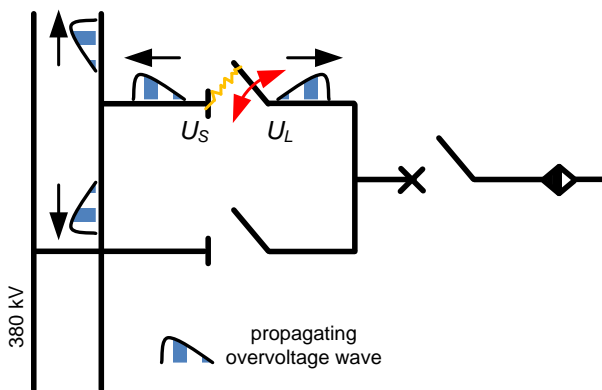
Slow-front transients are caused by switching operations like line or transformer energization and has a frequency in the range of 200 up to 20000 Hz. Their magnitudes and rise times are very dependent on various factors, like system earthing, type of load that is switched on and off as well as presence of overvoltage mitigation devices, like RC snubbers and surge arresters.

Lightning overvoltages are in the group of fast-front transients caused by atmospherical electric discharge into an overhead transmission line. Frequency of this phenomenon is in the range of 20 kHz up to 1MHz. Those overvoltages are a significant concern in high voltage power systems, since they generate an severe overvoltage wave, which propagates along the system and can cause failures of working machines and apparatus. Due to that fact, surge arresters with appropriate ratings are installed, which can significantly reduce magnitudes of this overvoltages [2, 3].

Oscillations with the highest frequencies are called Very Fast Transients and are a results of disconnector operating in GIS substations. This phenomenon was explained in details in further part of this article.

3. VFT PHENOMENON DESCRIPTION

During the closing operation of the disconnector in adjacent bay of GIS substation (Fig. 2) an electric arc occurs between the contacts. This spark results 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 significant influence on that effect has so called *trapped charge*, which is a capacitive charge at the disconnector load side. The worst case conditions occur, when the trapped charge is equal to -1 p.u. of nominal system voltage, whereas the cosine source side voltage is equal to +1 p.u. It results in highest potential difference between contacts during the spark occurrence, which leads to generation of significant overvoltages.



U_S – voltage at disconnector source side
 U_L – voltage at disconnector load side

Fig. 2. VFT generation principle – disconnector operating in the GIS substation

4. 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 1.

Table 1. 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 3.

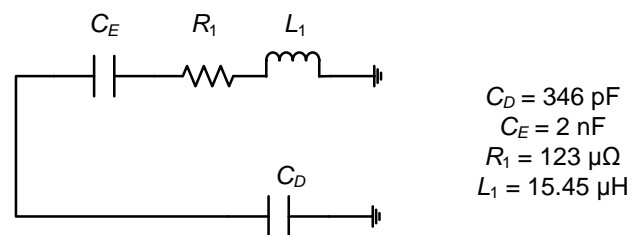


Fig. 3. High frequency model of the HV transformer side; C_D – HV side windings capacitance, C_E , R_1 , L_1 – capacitance, resistance and inductance of HV bushings

During the GIS disconnector closing, 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 during 4 ns, according to formula (1):

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

where: $\tau = 0.6 \cdot 10^{-9} \text{ s}$.

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.

5. EXEMPLARY VFT ANALYSIS OF 380 KV GIS SUBSTATION

An exemplary 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 4. It consists of 280 MVA power transformer that is energized through overhead transmission line interconnected to the substation with HV cable.

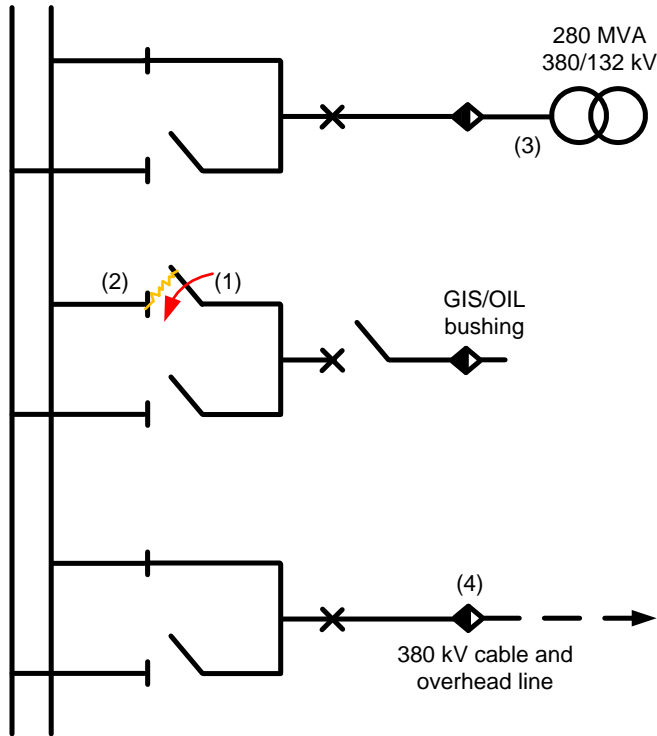


Fig. 4. 380 kV GIS substation – overall network diagram for VFT analysis

Singular switching operation (closing) of the disconnector *DS1* have been simulated in EMTP/ATP software. 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.). It has been also assumed, that the trapped charge at disconnector load side is equal to -1 p.u. Overvoltage waveforms have been obtained at following locations (according to Fig. 4):

- disconnector load side – position (1),
- disconnector 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):

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

6. SIMULATION RESULTS

As it was described in point 4, the disconnector 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, as it is visible in Figure 5.

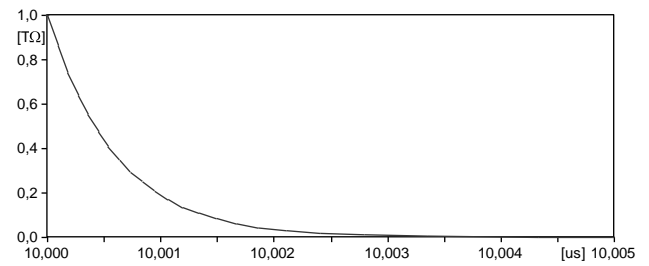


Fig. 5. Disconnector nonlinear resistance during closing event

Calculated overvoltage waveforms at specific locations of studied GIS substation have been illustrated in Figure 6.

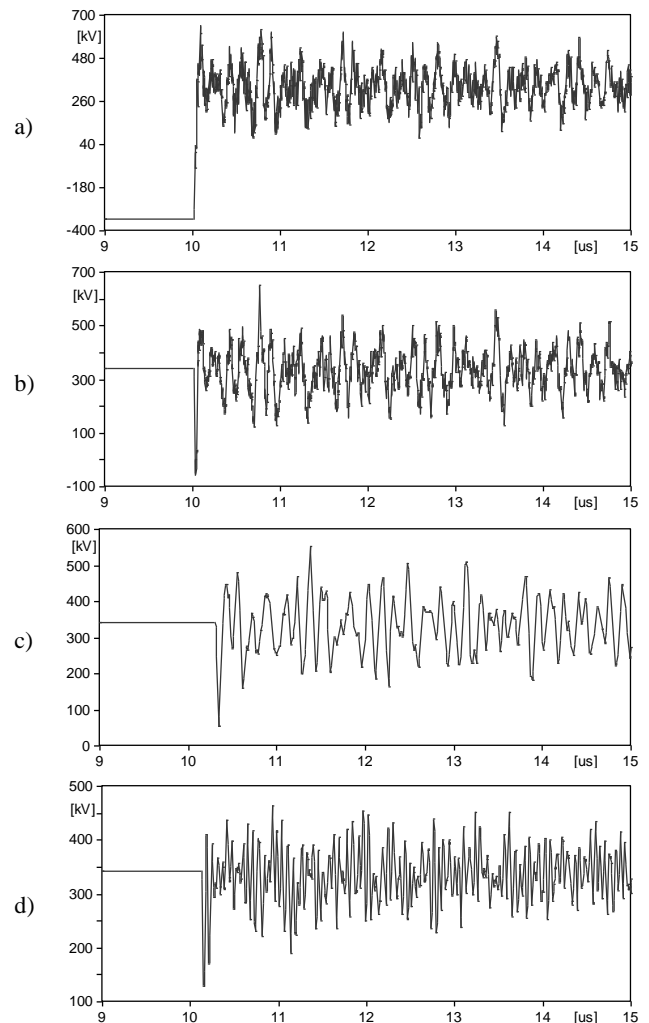


Fig. 6. VFT overvoltage waveforms at GIS different locations; a – disconnector load side, b – disconnector source side, c – transformer HV terminals, d – GIS-cable termination

As it is visible in Figure 6, 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 figure 1a it can be observed, that the disconnector load side is preloaded with trapped charge equal to -1 p.u. In figure 1c, which represents voltage waveform at transformer HV terminals 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 m/ μ s, which corresponds very well with assumed value of 290 m/ μ s. These values differ due to the presence of GIS equipment capacitances that smooth the overvoltage wave.

For each waveform, maximum overvoltage peak value have been obtained. Summarized results have been presented in Table 2.

Table 2. Simulation results summary

Voltage measurement locations	Maximum overvoltage peak values	
	[kV]	[p.u.]
disconnector load side (pos. 1)	649	1.89
disconnector source side (pos. 2)	655	1.91
transformer HV terminals (pos. 3)	551	1.61
GIS-cable termination (pos. 4)	464	1.35

As it has been presented in Table 2, the highest overvoltage peak value occurred at the operated disconnector 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 GIS. 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.

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, all reported values are within acceptable limits.

7. 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.

8. LITERATURE

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ANALIZA PRZEPIĘĆ SZYBKOZMIENNYCH W STACJACH WYSOKIEGO NAPIĘCIA IZOLOWANYCH GAZEM SF₆

Słowa kluczowe: odłącznik, operacje łączeniowe, przepięcia, stacja izolowana gazem SF₆

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, tzw. Very Fast Transients (VFT). Przepięcia te mogą być również efektem operacji łączeniowych dokonywanych odłącznikiem. Artykuł przedstawi zasady modelowania zjawisk przejściowych w stacjach GIS. W pracy zostanie ponadto pokazana przykładowa analiza przepięć generowanych poprzez operowanie odłącznikiem w stacji GIS.