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Electromagnetic disturbances in gas-insulated substations and VFT calculations

Akihiro Ametani*, Haoyan Xue, Masashi Natsui, Jean Mahseredjian

Ecole Polytechnique Montreal, Quebec H3C 3A7, Canada

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ABSTRACT

This paper is focused on the oscillating frequencies of very-fast transients (VFTs) generated by disconnector and circuit breaker operations in gas-insulated substations (GISs) related to electromagnetic disturbances (EMDs). Test results of the VFT amplitudes and oscillating frequencies are summarized, and the measured results have shown that there is no significant difference of the frequencies in the high-voltage main circuits and the low-voltage control circuits in the GISs. Modeling of GIS elements for VFT simulations by EMT-type software are explained, and simulation examples are demonstrated in comparison with test results. Also, FDTD (finite-difference time-domain) computations are performed, and the calculated results are compared with EMTP simulation results. If proper modeling is adopted, EMTP and FDTD results show a reasonable agreement.

1. Introduction

It is well-known that lightning strikes to a transmission tower nearby a substation and switching operations in a gas-insulated substation (GIS) produce high frequency surges. The dominant frequency components involved in the lightning surge are, in general, lower than 1 MHz. The switching surges due to disconnector (DS) or circuit breaker (CB) operation in the GIS contain the frequency components from some MHz up to more than 100 MHz, and are called "very fast transient (VFT)" or "very fast transient over-voltage (VFTO)" [1–3]. To investigate the VTF, a number of field and laboratory tests have been carried out [4–24]. Also, computer simulations of the VFT were performed, and modeling methods were investigated [25–31]. The measured and simulation results show that the VFT over-voltage reaches even 4 pu which becomes very important especially in a ultra-high-voltage (UHV) system because of a comparatively lower insulation level [1–3,19–21]. Various methods to damp the over-voltage have been proposed and the effectiveness are shown [7,12,23]. However, the oscillating frequency of the VFT is not much affected by the methods.

It has been pointed out that the high frequency components of the VFT are a main cause of electromagnetic disturbances (EMDs) in GIS control circuits [10,12,14–18,22,32–35].

This paper is focused on VFTs from the viewpoint of electromagnetic disturbances (EMDs). In Section 2, the voltage amplitudes and oscillating frequencies of the VFTs are summarized based on field and laboratory tests described in [4–24]. The measured results are categorized in the high-voltage main circuit of GISs, in the metallic enclosures and in the low-voltage control circuits. Section 3 explains modeling of GIS elements for VFT simulations by existing transmission line (TL) approaches, i.e. EMT-type software [36–39]. Then, calculated examples are demonstrated including a comparison with test results. In Section 4, an FDTD (finite-difference time-domain method [40,41]) computation is performed, and computed results are compared with EMTP results. Section 5 summarizes the investigated results in this paper.

2. Frequencies

Table 1 summarizes the measured results of the amplitudes and frequencies of VFTs. In the table, references, the rated voltage of GISs, VFT frequency and amplitude are shown. In (a) and (b), the amplitude is given by pu (per unit), while in (c) it is given by a peak-to-peak voltage.

It is observed in Table 1(a) that the VFT frequencies in UHV GISs are lower than those in lower voltage GISs except those given by Ref. [19]. Only few references show measured results of the VFT voltages and frequencies on the metallic enclosure (duct, tank or pipe) of the GISs. The measured voltages range from 0.1 to 0.7 pu in Table 1(b), because the pipe voltage is determined by mutual surge

* Corresponding author.
E-mail address: aametani@mail.doshisha.ac.jp (A. Ametani).

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Table 1
Summary of measured frequency and amplitude of VFTOs in GIS.

Ref. no	[5,6,13]	[10]	[23]	[24]	[12]
(a) High-voltage main circuit					
Rated [kV]	500/550	550	500	500	110/800
Frequency [MHz]	1–140	10–50	8–100	5–60	5–25
Voltage [pu]	1.2–3.0	2.7	–	–	1.2–1.7
Ref. no	[7]	[19]	[20]	[21]	–
Rated [kV]	UHV	1100	1100	1100	–
Frequency [MHz]	1–5	2–31	0.25–2	8–118	–
Voltage [pu]	2.4–3.0	1.35	1.05–1.62	1.82–2.19	–

Ref. no	[5]	[10]
(b) Metallic enclosure (duct, tank or pipe)		
Rated voltage [kV]	500	550
Frequency [MHz]	2.5–10	2–50
Voltage [pu]	0.1	0.1–0.7

(c) Low-voltage control circuit, Ref [16] (13 GISs/58 test cases)						
Rated [kV]	66/77			275		
Circuit	CT	VT	Control	CT	VT	Control
Frequency [MHz]	45–55	8	8–55	5–70	10–20	5–70
Peak to peak voltage [V]	20–600	20–120	10–100	80–700	10–600	60–220
Rated [kV]	500/550			1000		66–1000
Circuit	CT	VT	Control	VT		DC source
Frequency [MHz]	5–15	10–18	1–10	40–80		2–45
Peak to peak voltage [V]	100–240	10–200	10–100	60–450		80–700

impedance Z_{om} between the core and the pipe and core current I_c, i.e. $V_p = Z_{om} I_c$, and is dependent on the pipe grounding.

It should be noted that the frequency components in the pipe voltages are not much different from those in the core voltages in the same gas-insulated bus (GIB) [5,10].

Table 1(c) shows the peak-to-peak voltages and frequencies measured at the CT (measuring current transformer) secondary circuits, VT (measuring voltage transformer and capacitive voltage transformer = CVT) secondary circuits, digital/electronic control circuits and DC source circuits for the control circuits collected from 13 GISs in Japan [16]. Altogether 58 test cases are collected. The voltages range from 10 to 700 V with the frequencies from 1 to 80 MHz. It is observed that the VFT frequencies measured in the low-voltage circuits in Table 1(c) are lower than those measured in the high-voltage circuits in Table 1(a) and (b). The lower frequency components are estimated to be caused by wave deformation, not necessarily attenuation, along control cables with the length of more than 50 m connecting the CTs and VTs and the control circuits [16,30]. However, the frequencies up to 80 MHz are observed. The high frequency components have resulted in malfunctions of control circuits, EMDs, which occasionally caused system operation troubles [16–18].

In summary, Table 1 has made clear the significance of VFTs, not only for the insulation coordination of GISs especially in a UHV system [1–3] but also for EMDs due to malfunctions of low-voltage control circuits in GISs [32–35].

3. Modeling and EMTP calculations

This chapter first describes modeling of various elements/components of a GIS for VFT simulations by EMT-type software based on a transmission line (TL) approach [36–39]. Then, simulation examples are demonstrated including a comparison with measured VFT voltages.

3.1. Modeling of GIS elements/components

Ref. [25] describes the basic concepts for modeling GIS elements for VFT simulations by EMT-type software. Ref. [26] summarizes modeling methods of various elements/components involved in the GIS. Ref. [27] gives the values of equivalent capacitances of GIS spacers, bus open-end, CT, VT etc., and surge impedances of DS, CB, a bushing and an XLPE cable. Ref. [28] shows modeling of GIBs connected to a main bus, pipe grounding with arresters, etc. Ref. [29] explains modeling of mutual coupling between an overhead control cable and a grounding mesh in a substation. Ref. [30] shows modeling of a VT connected to the control cable and mutual coupling between the control cable and the GIB. Ref. [31] describes a detailed model of a CT.

Summarizing the above references and the authors' experiences, the following remarks are made for VFT simulations by EMTP.

(1) For VFT frequencies are very high, the earth is assumed as perfectly conducting ($\rho_e = 0$) or an Al plate can be assumed as the earth as often adopted in a laboratory test. In a very high frequency region, the coaxial mode is completed within the pipe and the pipe conductor becomes a complete shield. Thus, the earth effect is hardly observed in measured and simulation results. The fact has indicated that no frequency-dependent model of a conductor is necessary in an EMTP simulation. Further, only a core conductor with the coaxial propagation mode parameters is enough to perform a VFT simulation by EMTP, especially when both ends of a pipe are grounded.
(2) Pipe grounding has to be carefully considered. The waveform of a pipe voltage is affected by the grounding very much, although the core voltage is less influenced.
(3) A branched GIB (branch) causes a high frequency oscillation and a resultant surge waveform becomes very oscillatory. However, a measured waveform is entirely dependent on the sampling time (highest frequency) of an oscilloscope used for the measurement. If necessary, a branch can be represented by capacitance C_b [42].

$$C_b = 1/(z_{oc} c_c)\ [\mathrm{F/m}] \tag{1}$$

where z_{oc}: coaxial mode surge impedance, c_c: velocity.
(4) A charged GIB involves a dc voltage component which cannot be handled by EMTP. The dc voltage is represented by a low frequency ac voltage.
(5) The length of a lead wire connecting a source and a GIB core and grounding a GIB pipe is comparatively large for the GIB