Mitigation of Transient Overvoltages Generated Due to Switching Operations and Lightning in Gas-Insulated Substation (GIS) Without Extra Limiter

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Abstract: Gas-insulated substations (GIS) have different specifications in proportion to air-insulated substations. Transformer failures related to lightning and switching are often reported in the gas insulated substation (GIS). This problem is the voltage magnifications due to reflections of switching and lightning surges at various junctions within the GIS. Thereby overvoltages in GIS are more important than air-insulated substation. There are methods to suppress the stresses created by lightning and switching in the GIS. However, these methods are suitable before installing the substation and during the substation design period. This paper presents feasible methods for mitigation of the overvoltage magnitude. The advantages of the proposed methods are their simplicity and low cost for implantation along with producing minimal changes in the installed GIS.

Keywords: Gas-insulated Substations (GIS), Very fast transient overvoltages (VFTOs), Very fast transient currents (VFTCs), Transient Overvoltages, Switching operations, Lightning Overvoltages, Mitigation.

1 Introduction 1

Gas insulated substation (GIS), which is filled with pressurized SF6 gas for electrical insulation as well as for arc extinction, is widely used in electric power system in recent decades because of the advantages such as compact size, protection from pollution, a few maintenance, and high reliability [1].

In spite of these merits, GIS has its unique problems, among which is the voltage magnifications due to reflections of such switching and lightning surges at various junctions within the GIS [2].

Though switching and lightning surges have been reduced to an acceptable level in modern substation insulation coordination, still transformer failures related to lightning and switching operation are often reported.

Two possible transformer failure modes may happen in GIS. The transformer main insulation (the insulation between HV winding and LV winding, HV winding and core, or HV windings) will be threatened because of the large magnitude of the switching and lightning surges. On the other hand, the insulation between turns at the beginning of the HV winding is often disproportionally more stressed because of the large potential gradient appearing in the initial voltage distribution. It is possible that switching and lightning overvoltage may excite partial winding resonance in the transformer windings [3, 4].

Hence, power transformers may be exposed to a large number of transients due to switching and lightning surges, which may accelerate aging of transformer insulation and reduce transformer life.

Very fast transient overvoltages (VFTOs) generated due to switching operations in gas-insulated switchgear (GIS) and the associated very-fast transient currents (VFTCs) radiate electromagnetic (EM) fields during its propagation through the coaxial GIS bus section. The transient electromagnetic fields, in turn, leak out into the external environment through discontinuities such as gas-to-air bushing, gas-to-cable termination, nonmetallic viewing ports, insulated flanges, etc. and get coupled to the control equipment or data cables present in the GIS [5].

There are methods to suppress the stresses created by VFT from the source side. Ferromagnetic rings and resistor can be mounted on the conductors linked to the disconnector from both sides in order to effectively suppress both the steepness and the amplitudes of VFT [6]. Also extra arrester is a method for mitigation of lightning overvoltage. However, these methods are

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suitable before installing the substation and during the substation design period. This paper presents feasible methods for suppression of the overvoltage magnitude caused by VFT and lightning at the power transformer. Simplicity, low cost implementation as well as minimum changes in the installed GIS (which are currently under operation) are the main characteristics of these methods.

2 Modeling of GIS Components

Due to the traveling nature of the transients the modeling of GIS makes use of electrical equivalent circuits composed by lumped elements and especially by distributed parameter lines, defines by surge impedances and traveling times [7]. The inner system, which consists of the high voltage bus duct and the inner surface of the encapsulation, has been represented thoroughly by line sections modeled as transmission lines with distributed parameters.

Table.1 displays the electrical equivalent circuits and related information for modeling of GIS component. Figures 1 and 2 show the single-line diagram and Electrical equivalent circuit of a 245 kV GIS. Also the trapped charge is considered at 1.0 p.u.

During the closing operation of switches, the sparks is modeled by a fixed resistance in series with an exponentially decreasing resistance [9].

$$R(t) = R_0 e^{-t/\tau} + r \qquad (1)$$

In the lightning study, the component modeling is the same as in the switching case, except for power lines and surge arresters. The arrester is modeled as a nonlinear resistance, taking into account different spark over voltages and V–I characteristics according to the behavior of the time to crest of the incoming waves [10]. Its MCOV (maximum continuous operating voltage rating) is 140 kV.

Computer simulation has been done using the alternative transients program (ATP), a widely used version of EMTP [4]. In VFT and lightning overvoltages study, computer simulation has become widely adopted and is a powerful technique [2-7].

3 Fast Transient

Lightning overvoltage is a phase-to-ground or phase-to-phase overvoltage produced by one specific lightning discharge. The lightning overvoltages have duration between 1 and 100 microseconds and a wave front between 1 and 5 microseconds.

The wave shape of the lightning current is different from the voltage produced at the point of contact of the lightning stroke. The lightning conditions and specifications are shown in the Table 2. The steepness of the stroke current and its rate of decay were determined based on the guide lines given in reference [1].

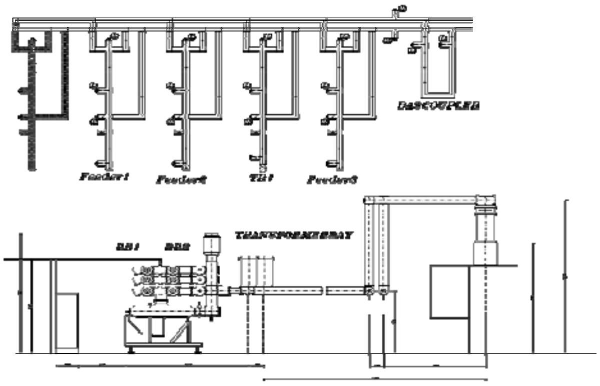


Fig. 1 Single-line diagram of a 245 kV GIS

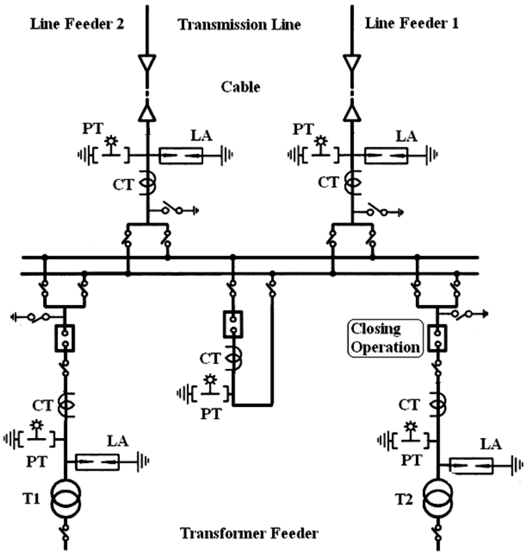


Fig. 2 Electrical equivalent circuit of a 245 kV GIS

Table 1 Electrical equivalent circuit [7],[8]

Components	NOTES
GIS Bus Bar	z_0 = 70 ohm v = 270 m/us
CB, DS, and Earthing Switch	In the closed position: impedance (70 ohm)
	In the open position: capacitance (4pF)
Potential Transformer (PT)	300 pF
Current Transformer (CT)	300 pF
Capacitive Voltage Transformer (CCVT)	5 nF
Bushing	100 pF
Power Transformer	2 nF
Arrester	Discharge Voltage (10kA):870kV
Cable	R_0 = 0.0010679 ohm/m z_0 = 30 ohm v = 165m/us

Table 2 The lightning condition and specification

Peak Current (kA)	Time to Crest (μs)
50	1.5
75	1.75
100	2.0
150	2.25
200	2.5

In this section, lightning overvoltages are simulated for lightning that directly striking the transmission line. This part is corresponding to the situation where bus coupler was opened and lightning is struck on the tower near the GIS. In order to simulation under the worst condition, it is considered that lightning was happened on the phase A and at the crest of negative polarity. Table 3 describes the lightning overvoltages with the various intensity current at the power transformer, CT, PT and tower near the lightning struck.

Table 3 Lightning overvoltages at the different location

Peak Current (kA)	Transformer (MV)	Tower (kV)	CT (MV)	PT (MV)
50	1.1221	67.17	1.1361	1.3044
75	1.1401	101.19	1.1584	1.3731
100	1.2841	142.98	1.3208	1.4442
150	1.3573	208.61	1.3544	1.5685
200	1.3635	274.96	1.4049	1.6158

Factors are investigated such as effects of the number of surge arrester in the each feeder, system configuration and decreasing of number of surge arrester and costs, and terminal component. The impact of various modeling details as discussed above is examined under various stroke current levels.

3.1 Effect of Number of Surge Arrester

This part is corresponding to the situation where bus coupler was opened and lightning struck on the tower near the GIS. The lightning overvoltages are investigated in six cases that are listed in Table 4.

Table 4 Various substation layouts for number of surge arrester

Cases	Number of Surge Arrester
A-1	The arresters are disabled in the line feeder.
A-2	The arresters are disabled in the transformer feeder.
A-3	Original arrester configuration is applied as shown in Fig. 2.
A-4	An extra arrester is installed in the transformer feeder based on case (A-3).
A-5	An extra arrester is installed in the line feeder based on case (A-3).
A-6	An extra arrester is installed in the transformer feeder and in the line feeder based on case (A-3).

Figure 3 shows the effect of number of surge arrester on the overvoltage at the power transformer terminal due to direct lightning stroke. It’s clear that existence of extra arrester can cause decreasing of the overvoltage. In the cases 4, 5, 6 are observed that peak magnitude of overvoltage variation at the power transformer terminal with increasing of lightning current is fixed. Figure 4 shows clearly effect of extra arrester on the lightning overvoltage at the power transformer terminal. The observed overvoltage at the power transformer terminal can reach up much more than the transformer BIL of 3.35 (p.u), when the arresters are disabled in the line and transformer feeder. But disabled arresters in the line feeder can be worse than disabled arresters in the transformer feeder. Therefore existence of arrester at the incoming feeder is emphasized. Case (A-3) in Figure 4 shows clearly that the voltage at the power transformer terminal is still very high because of reflection, and can be up to 4.1 (p.u). It is worth noting, that even with the arrester installed, the lightning overvoltage seen at the power transformer terminal is still higher than the transformer BIL in the studied case. Hence, installing extra surge arresters is necessary for suppressing harmful lightning overvoltages.

3.2 Effect of System Configuration

Installing extra surge arresters is necessary for suppressing harmful lightning overvoltages. But it is difficult to install extra arresters near transformers due to space limitation in the site.

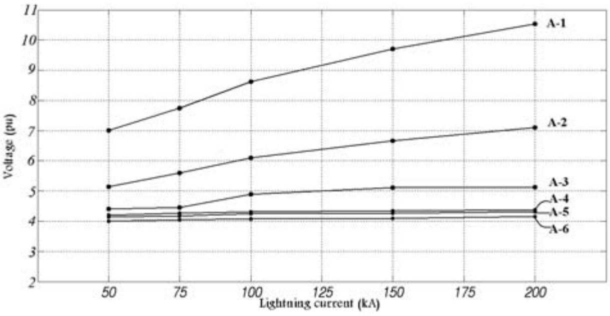


Fig. 3 Effects of number of surge arrester on the overvoltage at the power transformer due to direct lightning stroke

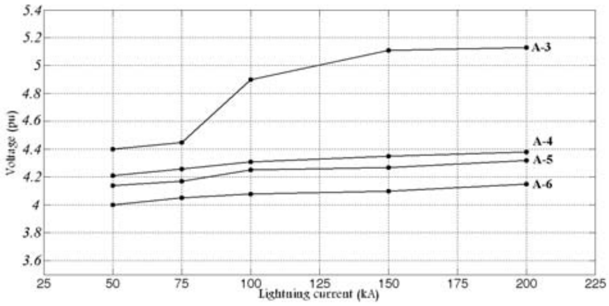


Fig. 4 Effects of extra arrester on the lightning overvoltage.

In order to suppress harmful lightning overvoltages at the transformer terminals, it can be used an approach without installation of extra arresters. In this way one can be closed circuit breaker of bus coupler or all of feeders associated with together and more transformers can be connected to the substation. In this section the lightning overvoltages are investigated in three cases that are listed in Table 5.

Table 5 Various substation layouts for new configuration

Cases	New Configuration
B-1	The arresters are disabled in the line feeder and bus coupler is closed
B-2	The arresters are disabled in the transformer feeder and bus coupler is closed
B-3	Original arrester configuration applied and bus coupler is closed.

Figure 5 shows effect of system configuration on the overvoltage at the power transformer terminal when bus coupler is closed. If bus coupler is closed, the lightning overvoltage at transformer terminals can be reduced to a level below the BIL in the studied case. Figure 6 compares effects of extra arrester and new configuration (bus coupler is closed or all of feeders associated with together). It’s clear that case (B-3) is lower than case (A-4) and case (A-5). Hence, appropriate configuration is even better than extra arrester in the feeder.

With more transformers connected to the network, more arresters must be also connected to the GIS, it is helpful for absorbing more lightning energy by the arresters; hence, it cause to reduce the maximum overvoltages at each transformer terminal.

3.3 Effect of Location of Surge Arrester and Cable

Due to absorbing more lightning energy by the arresters and negative reflection of cable, effect of location of surge arrester and cable is imported. This section is corresponding to the situation where bus coupler was opened and lightning struck on the tower near the GIS (Fig. 3). Original arrester configuration is applied as shown in Figure 7. The lightning overvoltages are investigated in five following cases that are listed in Table 6.

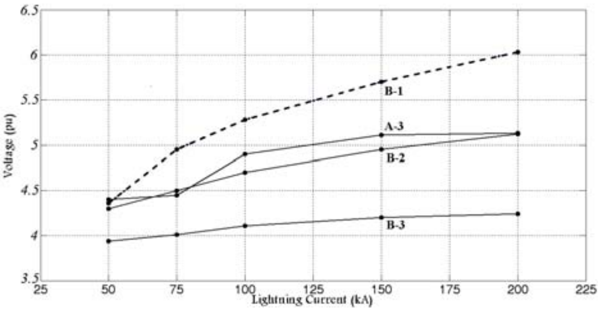


Fig. 5 Effects of System Configuration on the overvoltage at the power transformer terminal when bus coupler is closed.

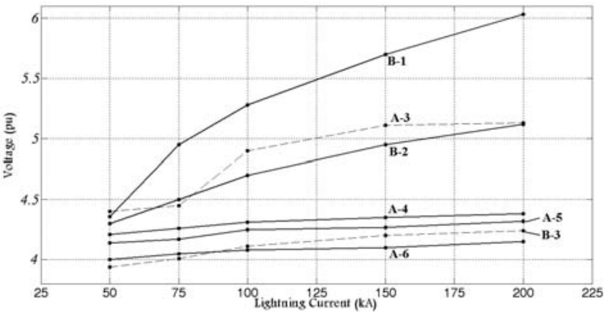


Fig. 6 Compares between effect of extra arrester and effect of new configuration (bus coupler is closed or more transformers can be connected to the substation).

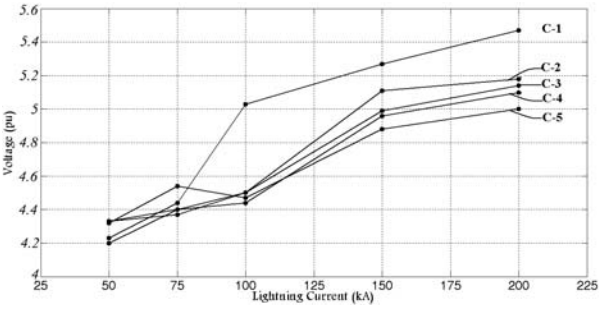


Fig. 7 Effects of location of surge arrester and cable on overvoltage at the power transformer terminal.

Table 6 Various substation layouts for new position of surge arrester and cable

Cases	New Configuration
C-1	The surge arrester situated in next of incoming cable
C-2	The surge arrester situated in 3/4 after incoming cable.
C-3	The surge arrester situated in 2/4 after incoming cable
C-4	The surge arrester situated in 1/4 after incoming cable
C-5	The surge arrester situated in before incoming cable.

Figure 7 shows effect of location of surge arrester and cable on the overvoltage at the power transformer terminal. It’s clear when the surge arrester is placed before of incoming cable, lightning overvoltages are decreased due to negative reflection.

3.4 Effect of the Terminal Component

The peak magnitude of lightning overvoltages at transformer terminals depends on the terminal component connected to the GIS. The terminal component can be a cable or an overhead transmission line or a gas-insulated line (GIL).

To understand the effect of different terminations on the peak magnitude of the lightning overvoltages, various substation layouts have been considered and are listed in Table 7.

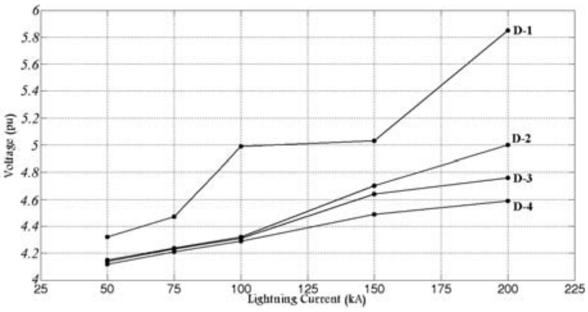


Fig. 8 Variations in peak magnitudes of the lightning overvoltages for various substation layouts.

Table 7 Various substation layouts for different terminals

Substation Layouts	The Terminal Component
D-1	Overhead Line
D-2	GIL
D-3	XLPE Cable
D-4	Two XLPE Cable in Parallel

Figure 8 shows variation in peak magnitudes of the lightning overvoltages for various substation layouts. The attenuation rate is high if the GIS is terminated with low impedance systems, such as cable, and the attenuation rate is low if the GIS is terminated with high surge impedance elements such as an overhead line. When the equivalent terminal components become smaller, the peak value of the overvoltage appearing at the transformer terminals is reduced dramatically due to negative reflection.

4 Very Fast Transient

Very fast transients (VFT) are generated during switching operation of circuit breakers (CB) and disconnectors (DS) within GIS [11]. Switching operations of the small 50 Hz capacitive (or inductive) no-load charging currents, when the circuit breakers are open, are accomplished by disconnectors. During these operations, both opening and closing, repetitive breakdowns in the form of re-strikes across the contacts occur. VFT have a very short rise time in the range of 4 to 100 ns, and followed by high frequency oscillations in the range of a few hundreds of kilohertz to about a few tens of megahertz [2], [12].

Figure 9(a) shows the magnitude waveform of VFTO at the power transformer. From this figure, it is seen that the peak magnitude of VFTO at the power transformer is about 307 kV. To understand the effect of distance from switching location on the peak magnitude of the VFTO, Figure 9(b) has been considered and the results are shown. The peak magnitude of VFTO at the nearby to switching operation is about 335 kV.

Figure 10(a) shows the magnitude waveform of VFTC at the CT. The peak magnitude of VFTC at the CT is about 7248 A. To understand the effect of distance from switching operation on the peak magnitude of the VFTC, Figure 10(b) has been considered and the results are shown. From this figure, it is evident that the peak magnitude of VFTC at the nearby to switching operation is about 9937 A.

4.1 Investigation of Terminal Component Impact on VFT

The peak magnitude of VFTO at transformer terminals depends on the terminal component connected to the GIS. The terminal component can be a cable or a gas-insulated line (GIL). The attenuation of VFTO amplitude with time is found to depend on the switching configuration and terminal component connected to the GIS [5].

Figure 11 shows variation in waveforms of the VFTO for various terminal components and lengths in the source side.

The amplitude is high if the GIS is terminated with high impedance systems, such as GIL, and the amplitude is low if the GIS is terminated with low surge impedance elements and high length such as cable-30m. Similarly, Figure 12 shows variation in peak magnitudes of the VFTO for cable and GIL terminal with various lengths.

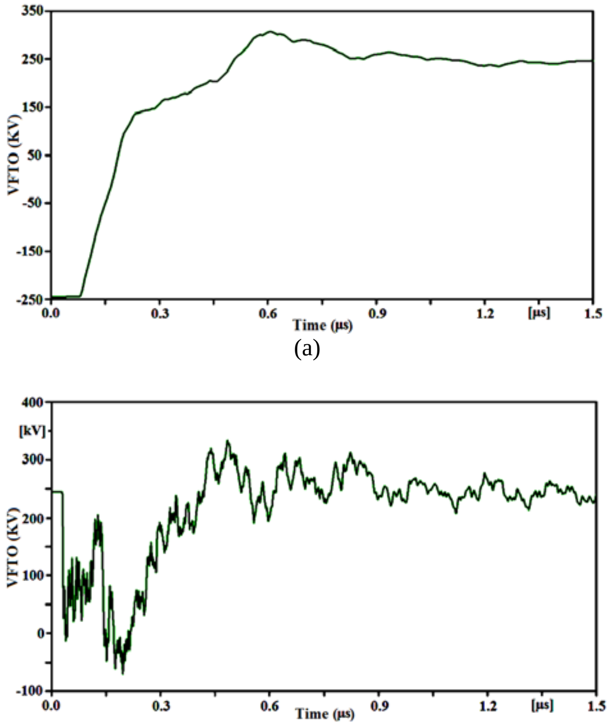
4.2 Investigation of Capacitance Impact on VFT

A problem is that VFTO always has a short rise time, which can cause an unbalance in voltage distribution in transformer windings. Under some special circumstances, the turn-to-turn voltage can arise close to the transformer basic insulation level [4].

However, a surge capacitor paralleled with the arrester may use as a wave modifier that damps the VFT front at transformer terminals and improve the VFT distribution along the transformer windings. It is also helpful for absorbing the sharp spikes of VFT due to CB restriking since surge arresters do not act quickly enough to prevent the switching transients with steep front. Therefore, installing an additional surge capacitor at transformer HV terminal might be very useful to mitigate the effects of VFT due to DS and CB restricting [3].

It is well known that surge capacitors have been applied in the protection of motors in LV and MV levels to reduce the risk of inter-turn insulation failure due to lightning or switching transients. However, there are several concerns when applying such surge capacitors in the protection of high voltage transformers as the case under study. These concerns are related to the capacitance value, capacity, cost, and possibility of failure of the surge capacitors themselves [4].

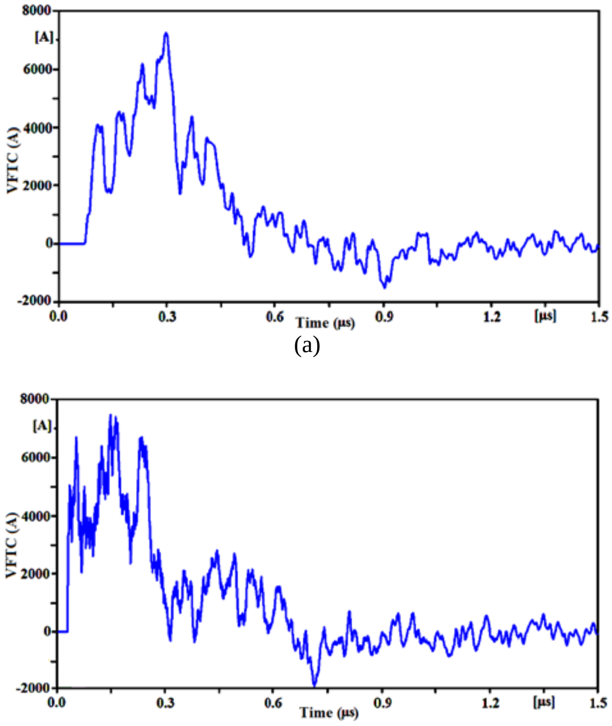
Figure 13 shows influence of increment of the capacitance on VFTO and VFTC. It is clear that with the increment of the capacitance, VFTO due to both DS and CB restriking will be further reduced. But peak magnitude of VFTC will be increased. There are such kind of HV capacitors could be easily obtained. There are such kind of HV capacitors could be easily obtained. For example, the capacitance of some 245 kV CCVTs is also 5 nF or capacitance of arrester is 0.2 nF.



(a)

(b)

Fig. 9 The magnitude waveform of VFTO (a) at the power transformer (b) at nearby to switching operation



(a)

(b)

Fig. 10 The magnitude waveform of VFTC (a) at the CT (b) at nearby to switching operation

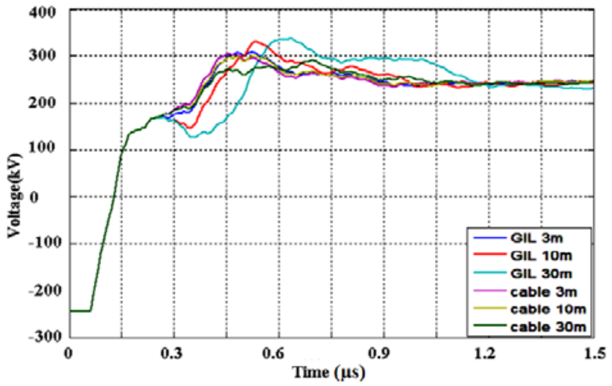


Fig. 11 Variation in waveforms of the VFTO for various terminal components and lengths in the source side

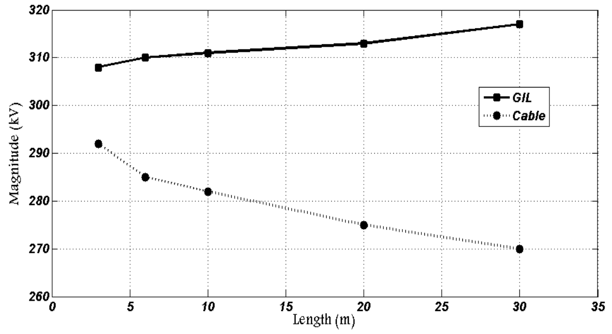


Fig. 12 Variation in peak magnitudes of the VFTO for cable and GIL terminal with various lengths.

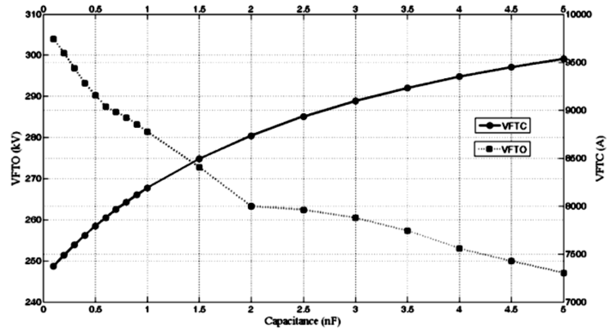


Fig. 13 Influence of the capacitance increasable on VFTO and VFTC

5 Conclusion

Magnitude of VFTO depends on distance from switching operation. Therefore switching operation is selected where it is nearby to notable equipment for investigation of VFTO on it.

Type and length of terminal components in GIS have considerable influence on VFTO.

A surge capacitor paralleled with the arrester may use as a wave modifier that damps the VFT front at transformer terminals and improve the VFT distribution along the transformer windings. It is also helpful for absorbing the sharp spikes of VFT due to CB restriking since surge arresters do not act quickly enough to prevent the switching transients with steep front.

Therefore, installing an additional surge capacitor at transformer HV terminal might be very useful to mitigate the effects of VFT due to DS and CB restriking. With the increment of the capacitance, VFTO due to both DS and CB restriking will be further reduced. But peak magnitude of VFTC will be increased. There are such kind of HV capacitors could be easily obtained. For example, the capacitance of some 245 kV CCVTs is also 5 nF or capacitance of arrester is 0.2 nF.

Installing extra surge arresters is necessary for suppressing harmful lightning overvoltages. But it is difficult to install extra arresters near transformers due to space limitation in the site. In order to suppressing harmful lightning overvoltages at the transformer terminals, it can be used an approach without installation of extra arresters. In this way one can be closed circuit breaker of bus coupler or all of feeders associated with together and more transformers can be connected to the substation. With more transformers connected to the network, more arresters must be also connected to the GIS, it is helpful for absorbing more lightning energy by the arresters; hence, it reduce to a level below the BIL in the studied case.

The peak magnitude of overvoltages at transformer terminals depends on the terminal component connected to the GIS. The attenuation of overvoltages amplitude with time is found to depend on the switching configuration and terminal component connected to the GIS. The attenuation rate is high if the GIS is terminated with low impedance systems, such as cable, and the attenuation rate is low if the GIS is terminated with high surge impedance elements such as an overhead line. When the equivalent terminal components become smaller, the peak value of the overvoltage appearing at the transformer terminals is reduced dramatically due to negative reflection.

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