Investigation of Very Fast Transient Over Voltages in Gas Insulated Substations

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Abstract—Gas Insulated Substations (GISs) have found a broad range of applications in power system over the last three decades because of their high reliability, easy maintenance, small ground space requirements, etc. Although GIS have been involved in power systems since long time ago, some of the problems are of more attention. These problems include generation and propagation of very fast transient over-voltages (VFTO) during switching of circuit breakers or disconnector switches or earth faults. The generated VFTO causes stress in the air-insulated switchgear and secondary equipment. This paper presents a modeling guideline for VFTO in GIS. The origin of VFTO, its propagation and impacts on GIS have been discussed in this paper. Estimation of VFTO has been carried out using EMTP-RV for various switching conditions. The variations in VFTO peak along the GIS bus nodes regarding the different magnitudes of trapped charges have been studied. The results indicate a distinct pattern of variation of VFTO peak along the nodes of the GIS bus in the case of DS operation as compared to that of CB operation. Moreover, the increase of trapped charge on the line increases VFTO levels. Finally, the beneficiary of several methods has been discussed to reduce VFTO amplitudes such as damping resistor, Ferrite rings and Nanocrystalline rings.

Keywords—EMTP; Very Fast Transient Overvoltage (VFTO); Gas Insulated Substation (GIS); Damping Resistor; Ferrite Rings; Nanocrystalline Rings; Trapped Charge

I. INTRODUCTION

Power system consists of various components such as power stations, substations, transmission lines and various loads, etc. With increase of demand of energy, more substations are needed to be installed. It is estimated that GIS require approximately 10% of the area required for conventional substations because of the dielectric strength of SF6 in GIS which is about 3 times more than air. The application of GIS has been increasingly requested by utilities since long time ago, some of these issues such as very fast transient over-voltages (VFTO). These transients are engendered within a GIS as the result of switching operation (opening or closing) of a disconnector switch [2], operation of circuit breaker, closing of grounding switch, or the occurrence of the fault. The contacts of a disconnector switch move slowly during opening and closing operations. While the dielectric strength between the contacts of the disconnector switch or breaker is overreached by the given over-voltage, pre-strike between the contacts occurs. This is a common event in GIS, which generates VFTO. It could enter the substation and may propagate inside the substation layout. The level and shape of VFTO depends on the GIS infrastructure. Consequently, the analysis of switching transients and VFTOs in GIS is desperately important.

According to IEC 60071-4, VFTO is characterized by rise time of 3 to 100 ns with oscillations at frequencies 0.3 MHz to 100MHz [9-14], [17]. Surge arresters cannot control these VFTOs due to their extreme rise time. However, the ZnO surge arrester may effectively limit the amplitude of VFTOs but cannot suppress the wave steepness due to its great rate of rise [17]. The magnitude of VFTO could reach 1.5pu to 2.0pu of the line-to-neutral voltage crest, or even 2.5pu in the worst case. These values are commonly below BIL of the components used in GIS. BIL is the basic impulse level which is the peak value of standard lightning impulse withstands voltage of system. The ratio of the BIL to the system voltage is lower in higher voltages; accordingly the VFT in GIS is of greater anxiety in high voltages [18]. Even though the magnitudes of VFTO are lower than BIL of the system, they cause reduction in the life of insulation in the system such as transformers due to their frequent occurrences [4]. Besides the over-voltages caused by VFT, the stress due to high frequencies may be critical for internal components like spacers.

This paper covers the estimation of VFTO at various locations in GIS for different switching operations. Furthermore, disconnector switching operations in comparison with the breaker switching is investigated. To estimate the VFTO magnitudes, the influence of trapped charge on the HV bus have to be taken into consideration. Therefore the variations of VFTO peak with different magnitudes of trapped charges have been studied. In addition, the impacts of several methods of suppressing such as damping resistor, ferrite Rings and Nanocrystalline ring on amplitude of VFTOs have been discussed.

II. ORIGIN OF VFTO IN GIS

VFTOs are generated in a GIS during disconnector or breaker switching operations, or by line-to-ground faults. In the switching operation in GIS, when the switch closes, the
distance between two contacts reduces and the electric field between them will rise until sparking occurs. The first reignition of arc occurs when the voltage across contacts overreach the breakdown voltage of the gas insulation. The first strike occurs inescapably at the crest of the power frequency voltage, due to the slow operating speed. Thereafter, current flow through the spark and charge the capacitive load to the source voltage and the potential difference across the contacts falls and the spark will eventually quench. When switch closes, the highest amplitude of voltage oscillation happens at the first arc reignition:

\[ U_1 = \sqrt[3]{2}V_n \]  

Where \( U_1 \) is the voltage amplitude at the first arc reignition; \( V_n \) is rated voltage of the power system [8].

When switch opens, the behavior is a complete reversal of the closing operation. In this case, the highest amplitude of voltage oscillation appears at the last arc reignition:

\[ U_2 = \sqrt[3]{2}V_n(1 + \exp(-\frac{1}{2\mu})) \]  

Where \( U_2 \) is the voltage amplitude at the last arc reignition and \( \mu \) is frequency of the power source and \( \tau \) is the leakage time constant of the electric charge in bus, which is determined by the bus capacitor and leakage resistance [8].

The rise time of the over-voltage resulting from strike depends on the field strength of the gap and is thus a function of the field utilization factor, \( h \), the insulation medium given by the breakdown field strength \((E/P)_0\) and the gas pressure \( p \). The rise time can be obtained by:

\[ t_r = 13.3 \frac{k_i}{(E/P)_0 ph} \]  

The Toepler spark constant is \( k_i=50kV/ns \) \( cm \). Rise time can be estimated in range of nanoseconds due to the high field of strength of the SF6 of \((E/P)_0=860kV/cm\) and the GIS gas pressure of up to 0.5 Mpa [1], [8].

III. MODELING OF GIS COMPONENTS FOR VFTO STUDY

In spite of all furtherance in electrical measurement techniques and equipment, quantifying the VFTO at such high frequencies (a few MHz) is still challenging. The best way to measure the quantity of the VFTO is to investigate switching operation in GIS; however it can cause irreparable financial damages to the system. Thus, actual measurement in the GIS during operation is not feasible. Consequently, modeling techniques and appropriate assumptions can provide reasonable accurate predictions of the VFTO magnitudes and frequencies and their rate of rise [5], [19-24].

Since VFTO contains substantially high frequency components ranging from hundreds of kHz to tens of MHz, most of the components have their capacitances dominating the other parameters [25]. Owing to VFTO’s short time maintenance, when closing or opening disconnector switch or breaker in one phase, other phases cannot sense the transient wave. Thus, the three phases can be put into a single bus bar or separate bus bars.

Modeling of GIS is accomplished by utilizing electrical equivalent circuits put together by lumped elements and delineated by surge impedances and travelling times. The quality of simulation depends upon surge impedance and travelling times, and also on quality of the model of each separate GIS component.

The typical length of a GIS bus is much smaller than a conventional substation and since the VFTO is like a travelling wave of particular velocity with reflections and refractions, the bus bar can be represented by a constant parameter line with velocity \( v \) and surge impedance \( Z \) [7]. The inductance and capacitance of a co-axial single phase in GIS bus is given by:

\[ L = \frac{\mu}{2\pi} \ln\left(\frac{b}{a}\right) \]  

\[ C = \frac{2\pi \varepsilon}{\ln\left(\frac{b}{a}\right)} \]  

\[ Z = \sqrt{\frac{L}{C}} \]  

Finally, the surge impedance is given by:

\[ Z = 60 \ln\left(\frac{b}{a}\right) \]  

Where, ‘a’ is the diameter of the HV bus and ‘b’ is the inner diameter of the enclosure and \( C \) is capacitance, \( L \) in inductance. According to IEC 62271-4 velocity is 0.95 of speed of light diameter of the enclosure.

The spark is modeled as an exponentially decaying resistance \((R_0e^{(-t/T)})\) in series with small resistance \((r=0.5\Omega)\) to take care of the residual spark resistance [7]. This is implemented using the time varying resistance in EMTP-RV. The time varying resistance is given by this equation:

\[ R(t)=R_0e^{(-t/T)}+r \]  

\( R_0 \) is taken \( 10^6 \) M \( \Omega \) and \( T \) is 1ns. The above equation gives a resistance whose value varies from very high value \((M \Omega)\) to low value of 0.5 \( \Omega \) within 30 ns [7].

The electrical equivalent circuits for different GIS components are tabulated in Table I [29].
### TABLE I. ELECTRICAL EQUIVALENT CIRCUITS FOR GIS COMPONENTS FOR REPRESENTATION OF VFT

<table>
<thead>
<tr>
<th>Components</th>
<th>Equivalent circuits</th>
<th>Notes</th>
</tr>
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<tbody>
<tr>
<td>Spacer</td>
<td><img src="image1.png" alt="Spacer Circuit" /></td>
<td>C=15 pF</td>
</tr>
<tr>
<td>Open End</td>
<td><img src="image2.png" alt="Open End Circuit" /></td>
<td>C=15 pF</td>
</tr>
<tr>
<td>Power Trans</td>
<td><img src="image3.png" alt="Power Trans Circuit" /></td>
<td>C=1.4 nF, Z=12.1 Ohm, L=20.9 mH, C=0.75 nF</td>
</tr>
<tr>
<td>Bushing</td>
<td><img src="image4.png" alt="Bushing Circuit" /></td>
<td>C=150 pF</td>
</tr>
<tr>
<td>ES</td>
<td><img src="image5.png" alt="ES Circuit" /></td>
<td>C=45 pF</td>
</tr>
<tr>
<td>LA</td>
<td><img src="image6.png" alt="LA Circuit" /></td>
<td>C=200 pF</td>
</tr>
<tr>
<td>SA</td>
<td><img src="image7.png" alt="SA Circuit" /></td>
<td>C=50 pF</td>
</tr>
<tr>
<td>CT</td>
<td><img src="image8.png" alt="CT Circuit" /></td>
<td>C=50 pF, Z=70 Ohm</td>
</tr>
<tr>
<td>XLPE Cable</td>
<td><img src="image9.png" alt="XLPE Cable Circuit" /></td>
<td>Z=30 Ohm, V=150 m/µs</td>
</tr>
<tr>
<td>DS</td>
<td><img src="image10.png" alt="DS Circuit" /></td>
<td>In the closed position: C=30 pF, Z=70 Ohm; In the open position: C=50 pF</td>
</tr>
<tr>
<td>CB</td>
<td><img src="image11.png" alt="CB Circuit" /></td>
<td>In the closed position: C=30 pF, Z=46 Ohm; In the open position: C=50 pF</td>
</tr>
<tr>
<td>Spark</td>
<td><img src="image12.png" alt="Spark Circuit" /></td>
<td>R=R₀e⁻t/T, T=1 ns, R₀=0.5 Ohm</td>
</tr>
<tr>
<td>Cross Junction</td>
<td><img src="image13.png" alt="Cross Junction Circuit" /></td>
<td>C=25 pF, Z=35 Ohm, L=450 mH</td>
</tr>
<tr>
<td>PT</td>
<td><img src="image14.png" alt="PT Circuit" /></td>
<td>C=100 pF</td>
</tr>
</tbody>
</table>

### IV. SIMULATIONS AND DISCUSSIONS

The approach is applied to a 400-kV GIS as shown in Fig. 1 which is a single-line diagram of a GIS. The mentioned GIS contain four lines. Two generators are placed in LINE 3 and 4. The incoming line of the GIS is comprised of an overhead line of 5-km length, an XLPE cable of 8-km length, PT, CT, lightning arrester (LA), earth switch (ES), disconnecter switch (DS), circuit breaker (CB), etc. The XLPE cable and transformers locations are assumed as source side and as load side, respectively.

Estimation of VFTO is carried out using EMTP-RV for various switching conditions. The variation in VFTO peak along the GIS bus nodes for disconnecter and circuit breaker switching operations is investigated; in the first condition, CB3 operate and in the next condition, DS4 operate when CB3 is kept open, respectively (See Fig. 1).

![Fig. 1. Single-line diagram of a Gas Insulated Substation [31].](image15.png)

The Scenarios in simulations are as follows:

1) CB3 operates (CB3 is closing after 0.4µs) in 400kV GIS
2) DS4 operates when CB3 is open in 400 kV GIS

The VFTO waveforms for the disconnecter and circuit breaker switching conditions in LL1, LL2, LL3, LL4 and LL5 are shown in Figs. 2 and 3. The nearest node to the switching point in the case of disconnecter switch operation is node LL4 and in the case of circuit breaker operation the closest node to the switching point is LL2.

It has been observed that the VFTO waveform has steeper front and correspondingly, higher frequencies as compared to other farther observation points in the GIS. As it is displayed in Fig. 2, node LL2 has higher frequency as compare to the other nodes. Likewise in Fig. 3, node LL4 has the same specialty.

In the case of circuit breaker operation, VFTO peak is found to be highest in node LL1 (at the end of the line). Its
value is 1.83pu just as it is shown in Fig. 4-a. According to Fig 4-b in the case of disconnector switch operation, VFTO peak in found to be highest in node LL4; near to the switching point. The value of VFTO peak magnitude in this node is 1.16pu.

It is investigated that the VFTO peak magnitudes are higher close to the switching point when disconnector switch operates, where as in the case of circuit breaker operation, VFTO peak magnitudes are higher at the end of the GIS and near the junction of GIS and overhead line. In addition, with comparison between VFTO levels of circuit breaker operation and disconnector switch operation, it is detected that a higher VFTO magnitudes occur in the case of circuit breaker switching operation. Correspondingly, in Fig. 5, it can be observed that a distinct signature pattern of the VFTO peak magnitude variation for disconnector switching operation as opposed to the circuit breaker switching operation is occurred.

B. Influence of Trapped Charge on GIS

The trapped charge remaining on load side of the disconnector must be taken into consideration, for the estimation of the VFTO stress. The trapped charge left on a floating section of switchgear depends on the disconnector switch construction [2]. In the case of high speed disconnectors, the maximum trapped charge could be as high as 1.0pu or even 1.2pu in the worst case [26], [27].

The variation of the VFTO magnitudes for 0.3pu, 1pu and 1.2pu of trapped charge is investigated in order to understand the exact influence of the trapped charge on the VFTO levels in GIS. The conditions considered are:

1) DS4 operates when CB3 is open with 0.3 pu trapped charge
2) DS4 operates when CB3 is open with 1 pu trapped charge
3) DS4 operates when CB3 is open with 1.2 pu trapped charge
It is concluded that when the trapped charge on the line increases, there is an increase in the VFTO peak magnitudes. But this increase is not proportional to the increase in the trapped charge magnitudes. As well the effect of trapped charge on VFTO peak magnitudes is higher in the line where the switching is done and specifically, at the nodes in the line where the switching operation is done (LL4 is the nearest node to the switching point). The variation of VFTO peak magnitudes for different trapped charges is demonstrated in Fig. 6.

C. Suppression Methods

Different methods are available to suppress the VFTO magnitudes. Mitigation VFTO by integration of a damping resistor and either by using Ferrite rings which are arranged around the inner conductor of the GIS are well proven technology [2], [28]. Third method of damping is by using Nanocrystalline rings which is a new method for mitigation of VFTO magnitudes.

In these cases, it is assumed that the substation is a 230kV GIS which is considered to estimate and compare suppression methods. Single-line diagram of GIS is demonstrated in Fig. 1. VFTO waveform when DS4 operated and CB3 is kept open in GIS without any mitigation methods at node LL3 is shown in Fig. 10-a whereas the VFTO peak in this condition is 1.232pu.

Accomplished investigations are as follows:

1) DS4 operates when CB3 is open with Damping Resistor in a 230 kV GIS

According to the maximum calculated VFTO and the necessary mitigation effect; the resistance of the damping resistor could be delineated. By increasing the resistance, VFTO magnitude can mitigate, but the dimension of the disconnector increases. Besides the energy absorption and the branching behavior must be taken into consideration. A flashover across the resistor may lead to a VFTO with comparatively higher amplitude as compared to a DS without such a damping resistor. Therefore it is required to overcome the drawback of such cumbersome designs by using other internal damping measures. Fig. 7 displays the equivalent circuit for damping resistor for simulation which its value based on previous research is 100Ω [29].

The effect of using damping resistor on the VFTO waveform when DS4 operate and CB3 is kept open in 230kV GIS at Node LL3 is demonstrated in Fig. 10-a. It is observed that by using Damping Resistor, VFTO peak decreases to 1.065pu. Furthermore, fewer level of VFTO magnitude is obtained by using damping resistor.

Fig. 7. Equivalent Damping resistor model

2) DS4 operates when CB3 is open with Ferrite Rings in a 230 kV GIS

The very high intensity of the magnetic field around the conductor causes the ferrite material to go to a completely saturation in this high magnetic field. The aftereffect of this saturation is damping effect reduction. It is possible to increase the magnetic field strength by layering of ferrite rings, but this can cause reduction in effective permeability. Therefore, the damping effectiveness of the whole ring arrangement decreases. Consequently, the damping effect of ferrite rings inside the GIS for HV applications is limited which is a malfunction of ferrite rings. Equivalent ferrite ring model is shown in Fig. 8. The value of R is 100Ω and L is 2mH.

The effect of the Ferrite Rings on VFTO waveform when DS4 operate and CB3 is kept open in 230kV GIS at Node LL3 is shown in Fig. 10-c and the value of VFTO peak in this case is 1.04pu. It is observed that the VFTO peak decreases more in compare to when damping resistor used in order to mitigate the VFTO magnitude.

Fig. 8. Equivalent Ferrite Ring model

3) DS4 operates when CB3 is open with Nanocristalline Rings in a 230 kV GIS

Like the ferrite rings, these rings are arranged around the inner conductor of the GIS. Experiments were accomplished by ABB Switzerland with different ring types, different sizes and different numbers of rings [30].

Fig. 13 displays the equivalent Nanocrystalline rings model for simulation where the values of R, L and C have been selected in order to make better suppression results. Therefore, the value of R is 150Ω and L is 0.002mH and C is 1pF [29],[30].

The effect of the Nanocristalline rings on VFTO waveform when DS4 operate and CB3 is kept open in 230kV GIS at Node LL3 is shown in Fig. 10-d and the value of VFTO in this case is 1.022pu. It is observed that the VFTO peak decreases more in compare to when damping resistor or ferrite rings used in order to mitigate the VFTO magnitude.

Fig. 9. Equivalent Nanocristalline Ring model

The comparison of different suppression methods and the VFTO magnitude in pu is given in Table II.

It has been observed in Fig. 10-a that VFTO peak magnitude is 1.232pu when DS4 operate and CB3 is kept open in 230kV GIS. Afterwards, the damping resistor of 100Ω is included in the switching operation of the disconnector and
it has been observed in Fig. 10-b that VFTO levels reduced to 1.065p.u. In addition lesser values of oscillation frequency occurred in the case of using damping resistor. Another method of suppressing VFTO’s have been carried out by modeling the ferrite rings and it has been obtained that the steepness and maximum peak values are reduced to considerable amount of 1.04p.u and very less values of oscillation frequency demonstrated in Fig. 10-c. It was correspondingly pointed that because of the saturation of Ferrite material, damping effect of ferrite rings inside the GIS for HV applications is limited. A new method has been described by using Nanocrystalline materials. It has been concluded that the third method had the best suppression effect. Fig. 10-d shows the effect of using Nanocrystalline rings.

The comparison of Variation of VFTO levels with different suppression methods is shown in Fig. 11.

Fig. 10. VFTO waveform when DS4 operate and CB3 is kept open in 230kV GIS at Node LL3. a)without any suppression methods b) with Damping Resistor c) with Ferrite Rings d) LL3 with Nanocristalline Rings

Fig. 11. Comparison of Variation of VFTO levels with different suppression methods

TABLE II. COMPARISON OF DIFFERENT SUPPRESSION METHODS

<table>
<thead>
<tr>
<th>Conditions</th>
<th>VFTO (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Suppression method</td>
<td>1.232</td>
</tr>
<tr>
<td>With Damping resistor</td>
<td>1.065</td>
</tr>
<tr>
<td>With Ferrite Rings</td>
<td>1.04</td>
</tr>
<tr>
<td>With Nanocristalline Rings</td>
<td>1.022</td>
</tr>
</tbody>
</table>

V. CONCLUSION

This paper investigated a general model for assessment of VFTO in GIS using EMTP-RV. It was observed that VFTO waveforms have steeper front and higher frequencies near the switching points. And there is a little trace of VFTO in farther points and other lines. In the case of circuit breaker operation, the VFTO peak is higher at the end of the line (near the junction of GIS with the overhead line) where the switching occurred. Where as in the case of disconnector switch operation VFTO peak is higher near the switching point and it decreases along the line where the switching has been done. Correspondingly, higher VFTO magnitudes occur in the case of circuit breaker operation as compared to disconnector switch operation. Besides, it has been observed that in comparison between the case of circuit breaker operation and disconnector switch operation, a distinct pattern of variation of VFTO peak along the nodes occur. The increase in the trapped charge on load side of the disconnector, causes augmentation.
in the VFTO magnitudes, but this increment is not proportional to the trapped charge increase. The results show that the VFTO levels are reduced with all methods. Hardness with the damping resistor is its heat losses during the operation and maintenance issues. Better suppression results acquired by using ferrite rings and furthermore this method overwhelmed the disadvantages of damping resistor. However, the malfunction of the ferrite rings is saturation difficulties. The ferrite rings are easily got into saturation under operating conditions. It was pointed that, by layering of ferrite rings increasing the magnetic field strength is applicable. But on the other hand layering of rings with a material of lower permeability also reduces the effective permeability. Therefore, the damping efficiency of the whole ring arrangement reduces. Consequently, the damping effect of ferrite rings inside the GIS for HV applications is limited. Further investigations have been made to suppress the VFTO in GIS using Nanocrystalline material which is proved that can provide better solution. The per unit data of VFTO without mitigation techniques and with different types of mitigation techniques are tabulated in Table. II.

REFERENCES