ANALSIS OF VERY FAST TRANSIENT OVER VOLTAGES IN GAS INSULATED SUBSTATIONS

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Abstract

Due to the opening or closing of circuit breakers and disconnect switches in Gas Insulated Substations (GIS), Very Fast Transient Over-voltages (VFTO) are generated. This paper describes the 500 kV and 750 kV GIS of power system. The variations of VFTO magnitudes at different points in 500 kV and 750 kV GIS during different switching operations have been calculated and compared by using Matlab/Simulink.

In this paper the effective factors on the level of VFTO is investigated and the beneficial approaches for the industry to finding the optimum approaches for VFT mitigation is presented. These factors are included residual charges, resistance, spark resistance and entrance capacitance of transformer.

Index Terms: *Gas Insulated Substation, Very Fast Transient Over voltages, Matlab/Simulink.*

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1. INTRODUCTION

The increase in demand for electricity and growing energy density in metropolitan cities have made it necessary to extend the existing high voltage networks right up to the consumers . Stepping down the voltage from transmission to the distribution level at the substation located near the actual consumers not only produces economic advantages, but also ensures reliable power supply. The following are the main reasons for use of gas insulated substation, GIS has small ground space requirements. Gas insulated Substations have easy maintenance (nearly zero Maintenance) Less field erection time & less erection cost. For underground power house of Hydro electric power project where space constraint is a major issue

This paper describes the 500 kV and 750 kV GIS of the power system. The variations of VFTO magnitudes at different points in 500 kV and 750 kV GIS during different switching operations have been calculated and compared by using Matlab/Simulink**.**

Very Fast Transients (VFT) belong to highest frequency range of transients in power systems. These transients are originated within a gas-insulated substation (GIS) any time there is an instantaneous change in voltage. This generally occurs as the result of the opening or closing of a disconnect switch, but other events, such as the operation of a circuit breaker, the closing of a grounding switch, or the occurrence of a fault, can also cause VFT. These transients have a very short rise time, in the range of 4 to 100 ns, and are normally followed by oscillations having frequencies in the range of 1 to 50 MHz.

During the operation of the DS, a small capacitor connecting to the breaker will be switched. The velocity of DS contacts is small (generally more than 0.6s), before the completely switching, the arc reignition or prestrike occurs, which is the main cause of VFTO. Figure.1. shows the equivalent circuit of VFTO during switching operation

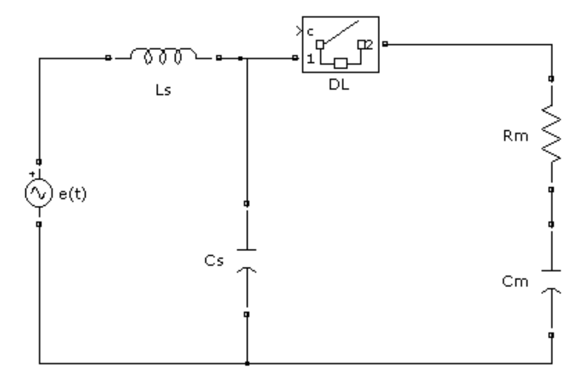

Fig -1: The Equivalent Circuit of VFTO during switching operation

Ls is the system equivalent reactance, Cs is the capacitor of system, DL is the circuit breaker, Cm is the bus capacitor and Rm is the leaking resistor of the bus.

During a dis connector operation a number of prestrikes-restrikes occur due to the relatively low speed of the moving contact. During closing as the contacts approach, the electric field between them will rise until sparking occurs. The first strike will almost occur at the crest of the power frequency voltage, due to the slow operating speed. T here after current will flow through the spark and charge the capacitive load to the source voltage. As it does, the potential difference across the contacts falls and the spark will extinguish.

2. EQUIVALENT MODELS

The quality of the simulation depends on the quality of the model of each individual GIS component. In order to achieve reasonable results even for longer time periods of some microseconds or for very complex GIS structures highly accurate models for each of the internal equipment and also for components connected to the GIS are necessary. Due to travelling wave nature of VFT, modeling of GIS components make use of electrical equivalent circuits composed of lumped elements and distributed parameters lines.

A GIS system comprising of an input cable, circuit breakers, Dis-connector Switch, Bus bar, power transformer, surge arrester. To simulate the Very Fast Transient over voltages occur at Disconnect switch in GIS, Matlab is used. The equivalent circuit of GIS is shown in figure 2.

Power transformer with bushing can be modeled by entrance Capacitance where entrance capacitance has been calculated in lightning test. Here the entrance capacitance of power transformer should be kept as a 5000pF. The surge impedance of a transmission Line is 350Ω and travel time is 300m/µs. The GIS Bus Bar can be represented as a lossless π- line for a 50 Hz frequency. The surge impedance is 80 Ω and travel time is 231m/µs [2]. The Cable can be represented as a lossless π-line for a 50 Hz frequency. The surge impedance is 68.8 Ω and travel time is 103.8m/µs. Metal Oxide surge arresters are used to protect medium and high voltage systems and equipment against lightning and switching over-voltages.
The surge impedance of a transmission line can be obtained from the relation

$$Z = 60 \ln \frac{b}{a} \;\; \Omega$$

Capacitance
$$C = \frac{2\pi \in_o \in_r}{\ln \frac{b}{a}}$$

Inductance
$$L = \frac{\mu \ln \frac{b}{a}}{2\pi} \;\; H$$

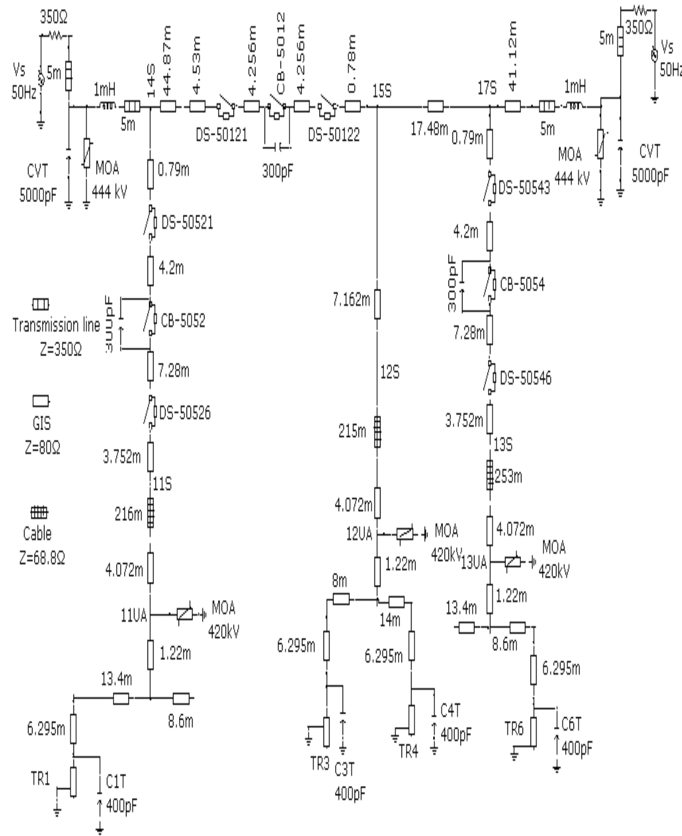

Fig -2: The Equivalent Circuit used for simulation

The MO Arrester obeys the equation

$$I = KV^{\alpha} \text{ , } \alpha>1$$

$$\frac{V_i}{V_{ref}} = K_i \left(\frac{I_i}{I_{ref}}\right)^{\frac{1}{\alpha_i}}$$

Where,

I current through arrester
V voltage across arrester
K ceramic constant (depending on arrester type)
α nonlinearity exponent (measure of nonlinearity).

The Characteristics of surge arresters are showed in Table 1 and Table 2

Table -1: Characteristics of 444kV surge arrester

Current(A)	Voltage(kV)
0.003	20000.0
628.0	1161.0

Table -2: Characteristics of 420 kV surge arrester

Current(A)	Voltage(kV)
0.008	594.0
20.0	674.5
10000	932.0

3. RESULTS AND DISCUSSIONS

Against the difference of switch operation mode and their position in GIS sub-station, we take three conditions to calculate Very Fast Transient Over-voltages [VFTO]. Such operation mode has two forms when opened and closed. When open recovery voltage between contacts is much higher and VFTO is higher correspondingly since the other contacts have residual charges. So followed operations are pointed to opened operation of DS.

A. VFTO caused by DS-50543.

When the Disconnect switch-50543 is opened before that the switches DS-50546 and CB-5054 are already opened then the VFTO level at Different points is shown in Table 3&4.

1) For 500 kV GIS

Source voltage is 550 kV.

Table -3: VFTO caused by operating of DS-50543 for 500kV GIS

Voltage to ground of bus-bar(kV)	V14s	535.1
	V15s	572.4
	V17s	706.3
Voltage to ground of surge arrester (kV)	V11UA	548.5
	V12UA	630.7
	V13UA	0.031
Voltage to ground of Transformer (kV)	VTR1	472.5
	VTR3	476.1
	VTR4	473.2

From data in table 3, we know that when opening of DS-50543 the maximal voltage to ground of bus bar near the switch reaches 1.73p.u.;the maximal voltage to ground of surge arrester reaches 1.54p.u.;the maximal voltage to ground of transformer reaches 1.16p.u.and the corresponding results are as follows.

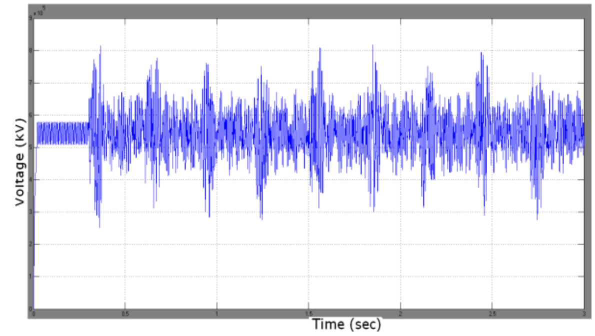

Fig -3: Voltage to ground of bus bar at 14S.

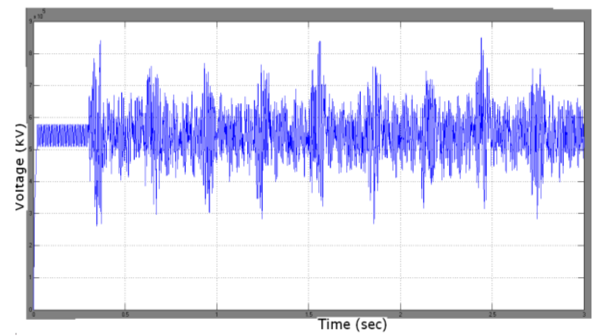

Fig -4: Voltage to ground of bus bar at 17S

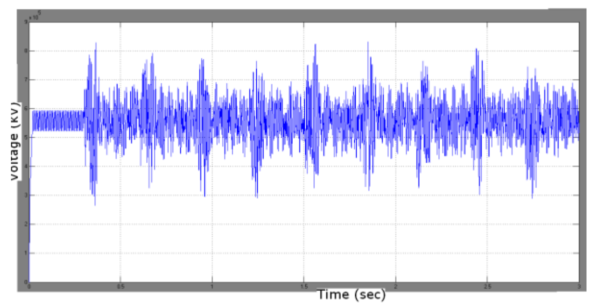

Fig -5: Voltage to ground of surge arrester at the end of transformer unit3&4

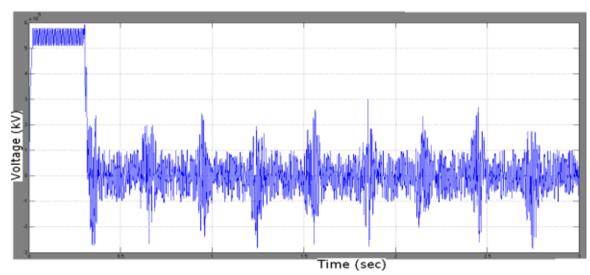

Fig -6: Voltage to ground of surge arrester at the end of transformer unit6

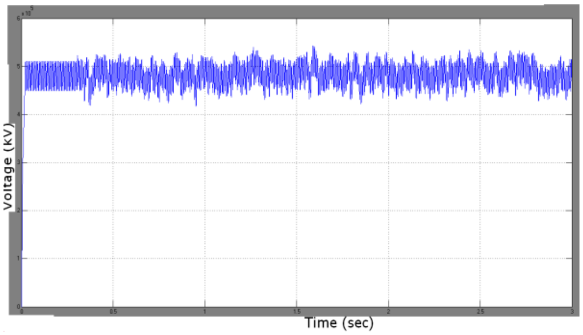

Fig -7 : Voltage to ground of transformer at unit 3

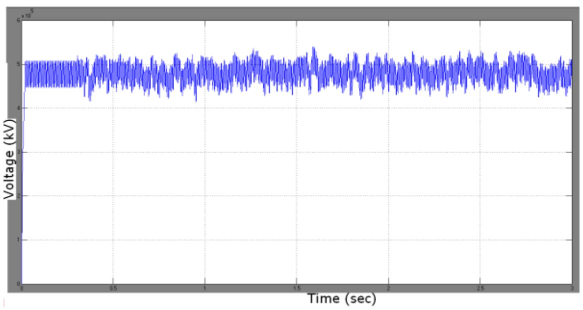

Fig -8: Voltage to ground of transformer at unit 4

2) **For 750 kV GIS**

Source voltage is 750 kV.

Table-4: VFTO caused by operating of DS-50543 for 750kV GIS

Voltage to ground of bus bar (kV)	V14s	729.7
	V15s	780.5
	V17s	963.1
Voltage to ground of surge arrester (kV)	V11UA	748
	V12UA	860.1
	V13UA	0.032
Voltage to ground of Transformer (kV)	VTR1	644.3
	VTR3	649.3
	VTR4	645.2

From data in table 4, we know that when opening of DS-50543 the maximal voltage to ground of bus bar near the switch reaches 1.57p.u; the maximal voltage to ground of surge arrester reaches 1.40p.u.;the maximal voltage to ground of transformer reaches 1.06p.u.and the corresponding results are as follows.

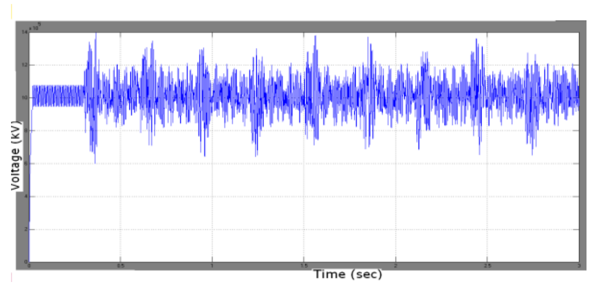

Fig -9: Voltage to ground of bus bar at 14S.

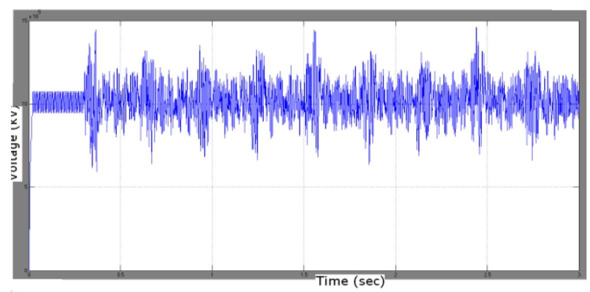

Fig -10: Voltage to ground of bus bar at 17S

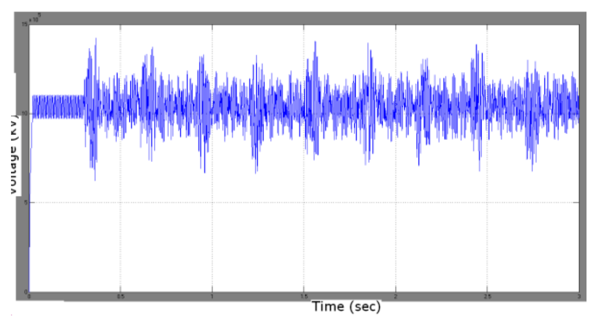

Fig -11: Voltage to ground of surge arrester at the end of transformer unit3&4

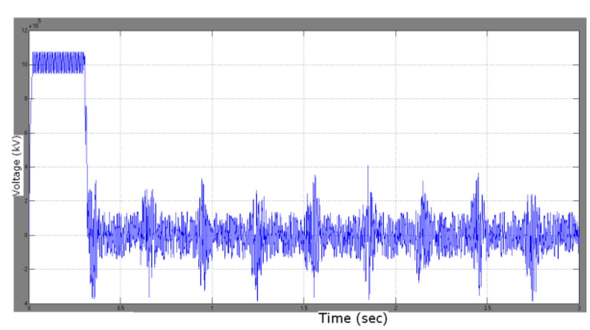

Fig -12: Voltage to ground of surge arrester at the end of transformer unit6

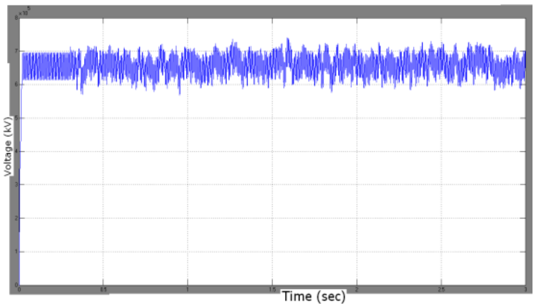

Fig -13: Voltage to ground of transformer at unit 3

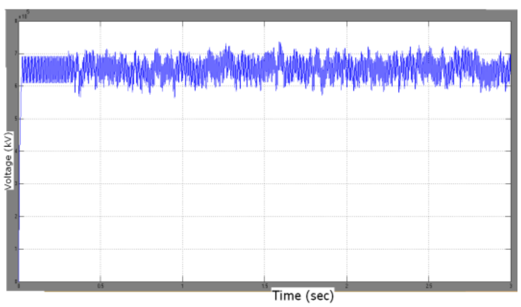

Fig -14: Voltage to ground of transformer at unit 4

B. VFTO caused by DS-50121 when DS-50122 open

When the Disconnect switch-50121 is opened before that the switches DS-50122 and CB-5012 are already opened then the VFTO level at Different points is shown in Table 5&6.

1) For 500 kV GIS

Table-5: VFTO caused by opening of DS-50121 open for 500kV GIS

Voltage to ground of bus bar (kV)	V14s	712.5
Voltage to ground of surge arrester (kV)	V11UA	676
Voltage to ground of transformer(kV)	VTR1	493.9

From data in table 5, we know that when opening of DS-50121 level of over voltages is much higher due to few current shunts circuit. The maximal voltage to ground of bus bar near the switch reaches 1.75p.u;the maximal voltage to ground of surge arrester reaches 1.65p.u.;the maximal voltage to ground of transformer reaches 1.20p.u

2) For 750 kV GIS

Source voltage is 750 kV

Table-6: VFTO caused by opening of DS-50121 open for 750kV GIS

Voltage to ground of bus bar (kV)	V14s	971.5
Voltage to ground of surge arrester (kV)	V11UA	921.9
Voltage to ground of transformer(kV)	VTR1	673.5

From data in table-6, the maximal voltage to ground of bus bar near the switch reaches 1.58p.u;the maximal voltage to ground of surge arrester reaches 1.50p.u.;the maximal voltage to ground of transformer reaches 1.09p.u.

C. VFTO caused by DS-50121 when DS-50122 closed

When the Disconnect switch-50121 is opened before that the switches DS-50122 is closed and CB-5012 is already opened then the VFTO level at Different points is shown in Table 7&8.

1) For 500 kV GIS

Source voltage is 550 kV.
From data in table 7, we know that when DS-50122 is still closed VFTO caused by opening DS-50121 will spread all over 500kv GIS.

Table-7: VFTO caused by opening of DS-50121 open when DS-50122 is closed for 500kV GIS

Voltage to ground of bus bar (kV)	V14s	562.5
	V15s	555.6
	V17s	517.1
Voltage to ground of surge arrester (kV)	V11UA	540.4
	V12UA	552.8
	V13UA	512.1
Voltage to ground of Transformer (kV)	VTR1	470
	VTR3	457.1
	VTR4	457.1
	VTR6	458.4

1) For 750 kV GIS

Source voltage is 750 kV.
From data in table 8, we know that when DS-50122 is still closed VFTO caused by opening DS-50121 will spread all over 750kv GIS.

Table-8: VFTO caused by opening of DS-50121 open when DS-50122 is closed for 750kV GIS

Voltage to ground of bus bar (kV)	V14s	767
	V15s	757.7
	V17s	705.2
Voltage to ground of surge arrester (kV)	V11UA	736.9
	V12UA	753.8
	V13UA	698.4
Voltage to ground of Transformer (kV)	VTR1	640.9
	VTR3	623.3
	VTR4	623.3
	VTR6	625.2

From the above tables we can observe that if we increase the supply voltage the transient voltage levels also increased.

4. EFFECTIVE FACTORS

The level of VFTO is determined by the factors including residual charges, series resistance, spark resistance, entrance capacitance of transformer.

A. Influence of Residual Charges.

When DS opens on line, it may be have some charges residual on the line that will influence the level of VFTO. Consider the first condition i.e. when DS-50543 is opened then the residual charges voltages of line side of transformer range from -1.0p.u to 0.5p.u,then the VFTO levels at different points are shown in Table 9,10,11,12

1) For 500 kV

Table-9: Simulation result of residual charges influence on VFTO at bus bars

	Voltage to ground of Bus-bar (kV)		
Residual Charges(p.u.)	V14s	V15s	V17s
-1.0	535.1	572.4	690.6
-0.5	511.5	539.4	632.6
0	488	506.5	568.7
0.5	464.4	473.7	504.7

In table-9, we can observe that the residual charges voltage of transformer range -1.0p.u. to 0.5p.u then the voltage to ground of bus bar levels are decreased. The maximal voltage to ground of bus bar at 17s range from 690.6 kV to 504.7 kV. So, the level of VFTO decreases along with the reduction of recovery voltage between contacts. The residual charges has function of suppression of VFTO.

From data in table-10, we can observe that The maximal voltage to ground of transformer at TR4 range from 469.2 kV to 447.9 kV. So, the level of VFTO decreases

Table-10: Simulation result of residual charges influence on VFTO at Transformers

Residual Charges(p.u.)	VTR1 [kV]	VTR3 [kV]	VTR4 [kV]
-1.0	472.5	472.2	469.2
-0.5	464.6	464.3	462.1
0	456.6	456.5	455
0.5	448.6	448.7	447.9

1) For 750kV

Table-11: Simulation result of residual charges influence on VFTO at bus bars

	Voltage to ground of Bus-bar (kV)		
Residual Charges(p.u.)	V14s	V15s	V17s
-1.0	729.7	780.5	949.9
-0.5	697.5	735.5	862.6
0	665.5	690.7	775.5
0.5	633.2	646	688.2

From data in table 11, we can observe that the maximal voltage to ground of bus bar at 17s range from 949.9 kV to 688.2 kV. So, the level of VFTO decreases along with the vary of residual charges. So, the residual charges has function of suppression of VFTO.

Table-12: Simulation result of residual charges influence on VFTO at Transformers

	Voltage to ground of Transformer(kV)		
Residual Charges(p.u.)	VTR1	VTR3	VTR4
-1.0	644.3	643.9	639.9
-0.5	633.5	633.2	630.1
0	622.6	622.5	620.5
0.5	611.8	611.8	610.7

The maximal voltage to ground of transformer at TR4 range from 639.9 kV to 610.7 kV. So, the level of VFTO decreases.

B. Influence of Resistance

1) For 500 kV GIS

Table-13: Simulation result of resistance influence on VFTO at bus bars

	Voltage to ground of Bus-bar (MV)		
Resistance(Ω)	V14s	V15s	V17s
100	3127	4373	8486
200	1564	2187	4243
300	1043	1458	2829
500	625.7	875	1698
1000	313.1	437.7	849.1

From table 13, we can observe that if the resistance is changed from 100 Ω to 1000 Ω, then the maximal voltage to ground of bus bar at 17S varied from 8486 MV to 849.1 MV. So, the level of VFTO decreases along with the increasing of resistance.

Table-14: Simulation result of resistance influence on VFTO at Transformers

	Voltage to ground of Transformer (MV)		
Resistance(Ω)	VTR1	VTR3	VTR4
100	1051	1044	951.7
200	525.6	522.4	476.1
300	350.5	348.4	317.5
500	210.5	209.2	190.7
1000	105.5	104.8	95.58

From table 14, we can observe that if the resistance is changed from 100 Ω to 1000 Ω, then the maximal voltage to ground of transformers at TR4 varied from 951.7 MV to 95.58 MV. So, the level of VFTO decreases along with the increasing of resistance.

2) For 750kV

Similarly for 750kV for increasing the series resistance the VFTO levels decreased. The simulation results are shown in the tables 15 &16.

Table-15: Simulation result of resistance influence on VFTO at bus bars

	Voltage to ground of Bus-bar (MV)		
Resistance(Ω)	V14s	V15s	V17s
100	4264	5963	11570
200	2132	2982	5786
300	1422	1988	3858
500	853.3	1193	2315
1000	427	595.9	1158

Table16: Simulation result of resistance influence on VFTO at Transformers

	Voltage to ground of Transformer (MV)		
Resistance(Ω)	VTR1	VTR3	VTR4
T 100	1433	1424	1298
a 200	715.7	712.3	649.2
b 300	478	475.1	433
l 500	287.1	285.3	260.1
e 1000	143.8	143	130.3

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C. INFLUENCE OF SPARK RESISTANCE

When restriking transient happens, spark resistance can have effect on damping over voltages. Spark resistance is an exponentially decaying resistance. Table 17, 18, 19 and 20 are the simulation results of the spark resistance influence of VFTO.

1) For 500 kV GIS

Source voltage is 550 kV.

From data in table 17, we can observe that if the spark resistance is varied from 0.1 to 200 Ω then the maximum voltage to ground of bus bar at 17s varied from 701.3 to 436.7 kV. similarly the maximum voltage to ground of transformer varied from 478.4 to 445.9 kV. So, the VFTO levels decreased along with the increasing the spark resistance.

Table -17: Simulation result of spark resistance influence on VFTO at bus bars

	Voltage to ground of Bus-bar (kV)		
Spark Resistance(Ω)	V14s	V15s	V17s
0.1	537.4	574.4	701.3
25	535.1	572.4	696.7
10	528.9	566.4	683.4
50	505.9	541.9	631.5
100	477	511.2	566.6
200	419.4	449.9	436.7

Table -18: Simulation result of spark resistance influence on VFTO at transformers

	Voltage to ground of Transformer(kV)		
Spark Resistance(Ω)	VTR1	VTR3	VTR4
0.1	472.8	472.7	478.4
25	472.5	472.2	469.3
10	471.4	470.9	468.2
50	466.6	465.5	463.5
100	460.0	458.8	457.6
200	448.6	445.3	445.9

2) **For 750 kV**

Table -19: Simulation result of spark resistance influence on VFTO at bus bars

	Voltage to ground of Bus-bar (kV)		
Spark Resistance(Ω)	V14s	V15s	V17s
0.1	732.8	783.2	956.3
25	729.7	780.5	950
10	721.3	772.4	931.9
50	689.8	738.8	861.1
100	650	697.1	772.6
200	571.9	613.4	595.5

Table -20: Simulation result of spark resistance influence on VFTO at transformers

	Voltage to ground of Transformer(kV)		
Transformer Entrance Capacitance(pF)	VTR1	VTR3	VTR4
5000	644.2	643.9	639.8
10000	621.5	628.9	625.8
15000	618.2	624.8	622.6
20000	614.8	620.6	619.4
25000	611.5	616.4	616.2

D.INFLUENCE OF ENTRANCE CAPACITANCE OF TRANSFORMER

The simulation results transformer entrance capacitance influence of VFTO is shown in tables 21,22,23,24.

1) When DS-50543 opened

a) For 500 kV GIS.

Table-21:Simulation result of transformer entrance capacitance influence on VFTO when DS-50543 opened.

	Voltage to ground of Transformer(kV)		
Transformer Entrance Capacitance(pF)	VTR1	VTR3	VTR4
5000	453.3	458.2	456.6
10000	455.8	461.2	458.9
15000	472.4	472.2	469.2
20000	450.9	455.1	454.2
25000	448.4	452	451.9

From data in table-21, we can observe that the entrance capacitance is changed from 5000 to 25000 pF, then the max. voltage to ground of transformer is changed from 456.6 kV to 451.9 kV, So, the VFTO levels decreased along with the increasing the entrance capacitance of transformer.

b) **For 750 kV**

Similarly in 750kV, the VFTO levels decreased along with the increasing the entrance capacitance of transformer.

Table-22: Simulation result of transformer entrance capacitance influence on VFTO when DS-50543 opened

Spark Resistance(Ω)	VTR1 [kV]	VTR3 [kV]	VTR4 [kV]
0.1	644.7	644.6	652.4
25	644.3	643.9	639.9
10	642.8	642.2	638.4
50	636.3	634.8	632
100	628.1	625.6	624.1
200	611.7	607.2	608.1

2) When DS-50121 opened(DS-50122 closed)

a) For 500 kV

Table-23: Simulation result of transformer entrance capacitance influence on VFTO when DS-50543 opened

	Voltage to ground of Transformer(kV)			
C (pF)	VTR1	VTR3	VTR4	VTR6
5000	470	457.1	457.1	458.4
10000	458.9	449.7	449.7	451.2
15000	456.6	447	446.9	448.7
20000	454.3	444.2	444	446.3
25000	452	441.4	441.2	443.8

b) For 750 kV

Table-24:Simulation result of transformer entrance capacitance influence on VFTO when DS-50543 opened

	Voltage to ground of Transformer(kV)			
C(pF)	VTR1	VTR3	VTR4	VTR6
5000	640.9	623.3	623.3	625.1
10000	625.8	613.3	613.2	615.3
15000	622.7	609.5	609.4	611.9
20000	619.5	605.7	605.5	608.6
25000	616.3	601.9	601.6	605.2

CONCLUSIONS

The 500 kV and 750 kV Gas Insulated Substation system had been modeled and studied for VFTO's by using Matlab/simulink. It can be concluded that as the source voltage is increased the VFTO levels also increased and also conclude that the factors residual charges, Spark resistance, resistance and the entrance capacitance have functions of Suppression of VFTO.

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