Svedberg Open
DISSEMINATION OF KNOWLEDGE

International Journal of Artificial Intelligence and Machine Learning

Publisher's Home Page: https://www.svedbergopen.com/



Research Paper Open Access

High Frequency Switching Transients in 420kV Gas Insulated Substation Due To Disconnector Operation

Naga Jyothi Marella[1,3*], C.V.K.Bhanu[2]

[1]PhD Scholar, Department of Electrical and Electronics Engineering, JNTUK, Kakinada, India. Email: nagajyothi_m@vnrvjiet.in Orcid ID:https://orcid.org/0000-0002-1476-8657
[2]Department of EEE, GVP College of Engineering, Visakhapatnam , India. Email: bhanucvk@gvpce.ac.in, ORCID ID: 0000-0002-2290-9392
[3]Department of EEE, VNR Vignana Jyothi Institute of Engineering & Technology, India.

ABSTRACT
Very Fast Transient Over voltages (VFTOs) are generated in GIS due to any switching operation but their effect is significant during opening and closing operation of Disconnector. VFTOs are significant especially in disconnector is due to two reasons- Due to slow operating speed of disconnector and Length of GIS bus bar is relatively small compared to AIS Busbar. Due to slow operating speed of disconnector, the sparks are generated and extinguished several times. The transients which are generated at the disconnector travel through the length of GIS bus bar. At the end of the bus bar, they get reflected and refracted many times in a very less time and will have frequency range in Megahertz. Hence these are called very fast transient over voltages.
VFTOs are of major concern for High operating voltage GIS in which ratio of lightning impulse withstand voltage and to system voltage decreases. As this ratio decreases, VFTOs cause many problems like insulation damage, secondary breakdown of GIS.
Thus, the detailed study of VFTOs is necessary for insulation coordination studies in GIS and for adopting mitigating methods. This detailed study of VFTOs is possible by modelling of each component of GIS using electrical equivalent circuits which provides accurate results.
In this paper VFT over voltages at various locations in a 420 kV gas insulated substation is analyzed using Electromagnetic Transient Program (EMTP-ATP). The peak value of VFTO is measured for different trapped charge values on the bus section. The maximum peak with a trapped charge of -1 P.U is 3.09 P.U. From the Fast Fourier Transform (FFT) analysis of the VFT overvoltage waveforms it has been found that the major frequency components lie in the range of 1 MHz to 70 MHz the effect of trapped charge, terminal components on VFTO magnitude and steepness is studied, the electrical equivalent of ferrite rings is also connected to the 420kV system to reduce the effect of VFTOs. In this paper a 420kV system is considered for VFTO study, circuit-based model is developed in EMTP-ATP.VFTOs are observed at different locations with Disconnector operation. The influence of switching conditions on VFTOs and various terminal equipment is also observed. Electromagnetic field associated with VFTCs is estimated using a field-based model in COMSOL multi physics software.

Keywords: Disconnector switching transients, VFTCs ,VFTOs ,EMTP-ATP, terminal components

1. INTRODUCTION

In any GIS, the VFTOs are generated from all the switching devices, but the VFTOs that are generated from disconnector are of major concern due to slow operating speed of disconnector [1]. The transients which are generated across the operating disconnector travel further on either side of it. As the transient moves, it encounters change in surge impedance at the line discontinuities and thus the transients experience multiple reflections and refractions. These reflected and refracted waves get superimposed and leads to the formation of VFTOs. Due to this reason mentioned above, several number of restrikes and prestrikes occurs during the time of closing and opening operation of disconnector. VFTOs mainly depend on the voltages on the either side of the disconnector. They also depend on:

- The sparks that occur across the contacts of the disconnector.
- The parameters of GIS components that are connected to the disconnector.

- The source side and load side voltages mainly determine the instant at which arc is produced across the contacts of disconnector.
- Us and Ul along with GIS components connected to disconnector will influence the peak value of VFTO.
- Sparks will have its influence on high frequency nature of VFTO waveforms.
- The sparks are generated across the contact gap whenever the voltage across the contacts exceeds instantaneous voltage.

Very fast transients are generated when there is a collapse of electric field between the contacts of disconnector. In a GIS, a large number of restrikes and prestrikes occur across the contacts when the disconnector switch is opened or closed. Each restrike and prestrike results in the travelling waves on the either side of disconnector. These so generated travelling waves will propagate through the shortest lengths of GIS bus ducts, were subjected to several reflections and refractions, when encountered by impedance changes in terminal components. Since the operating time of disconnector is about 3-6 seconds and it is known that one second of source voltage comprises fifty cycles. Generally, for each cycle, 1-2 VFTs are being generated. Hence, it is concluded that a maximum of 600 VFTs are produced for one closing or opening operation, Due to this reason disconnector operation is significant than Circuit Breaker operation for the generation of VFTOs in GIS[2].

Compared to the BIL of the system, their magnitudes are less, but their frequent occurrence results in the deterioration of the insulation and lessens its life [3]. It may also lead to ground fault, as a result of flash over phenomenon caused due to reduced dielectric strength of SF6 in presence of free metallic particles. Further, these VFTOs also affects the insulation if the GIS equipment such as transformers, by creating a stress on inter-turn insulation with enormously higher voltages. Considering, all these adverse effects caused by these transients, there is a need to estimate and analyze the magnitudes of these VFTOs generated when switching operations in GIS are in progress [4]. As the magnitudes of these VFTOs are dependent on different parameters say, trapped charge magnitude present in HV bus, layout of substation, switching point location etc., Hence, there is a need to study these parameters influence on VFTO magnitudes. Computer simulation of these switching operations becomes very advantageous and time saving, as the VFTO measurements over a very high frequencies are quite laborious [5]. Also, it is not preferable to commission the GIS plant without estimating the VFTO magnitudes, their rise times and adverse effects on various GIS components. Estimation of all these becomes very convenient and accurate using simulation.

2. MODELLING OF GIS COMPONENTS:

The system data have been presented in and the input details for VFTO study has been provided in Table 1. The modelling of various equipment in GIS is represented in, and the required surge impedance values calculated for simulation are given. The modelling of the GIS equipment for the VFTO study has been done as per the guidelines provided by Very Fast Transients Task Force of the IEEE Working Group on Modelling and Analysis of System Transients. Equivalent network diagram has been derived for the configurations with reference to the following cases for the VFTO analysis.The GIS Bus duct is modelled using eqn(1) [6].

$Z=60 \ln\frac{b}{a} \Omega$ (1) Where Z is the characteristic impedance of the distributed parameter line model, 'b' and 'a' are the inner diameter of the bus bar enclosure and diameter of the centre conductor, respectively. The characteristic impedance is 95 Ω for the substation bus ducts studied [7].

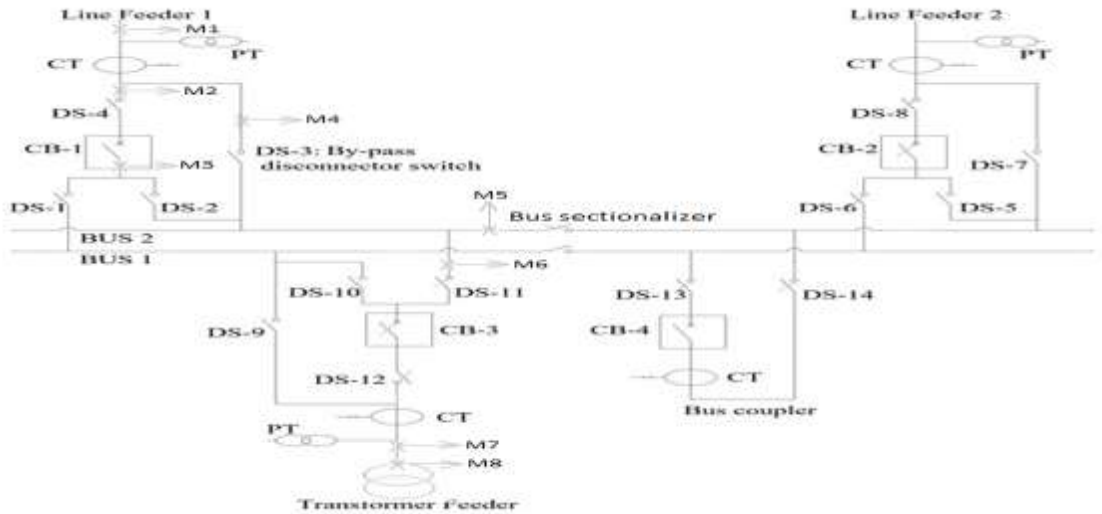


Fig1. Single line diagram of a 420kV GIS model

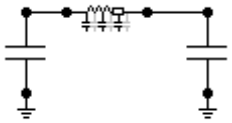
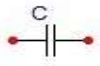
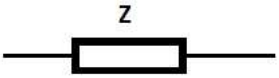
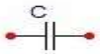
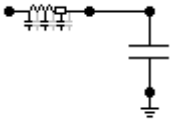
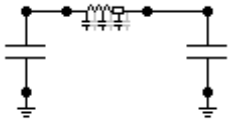
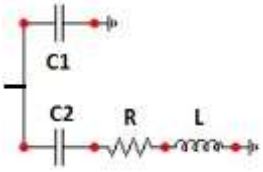
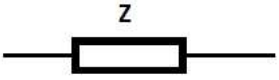
Dynamic resistance model is used for representing the arc in the disconnector and is given by the following equation. Single spark approach is used to create Disconnector switching operation.

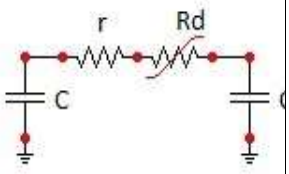
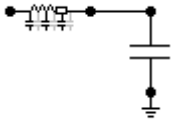
$$Rs = Rf + R0 * e^{-\frac{t}{T}} \quad (2)$$

Where R0 is initialized to a very high value of 1012 Ω, Rf is the residual series resistance and is taken as 0.5 Ω and T is taken as 0.6*10-9 s [8].

The model used for circuit breaker is presented in Table 1. In closed position, a lumped capacitance of 32pF to ground is used [9]. The transformer in the substation is modelled as shown in Fig. 4(b). It is represented by means of inductance, resistance, and capacitance of HV windings as well as capacitance of HV side bushing. Parameters are evaluated from the frequency response analysis of the transformer. Cable is represented by a surge impedance of 30 ohms wave velocity is taken as 172000000 m/sec. Gas Insulated Transmission Line is represented by a surge impedance of 70 ohms wave velocity is taken as 285000000 m/sec. OHL is represented by a surge impedance of 409 ohms wave velocity is taken as 3*108 m/sec [10].

Table 1 Equivalent Models for Components in 420kV GIS

GIS Components	Equivalent circuit	Equivalent parameter
Circuit Breaker (closed)		C= 32 pF Z=66 Ω
Circuit Breaker (opened)		C= 4 pF
Disconnector (closed)		Z=42 Ω
Disconnector (opened)		C= 4 pF
Potential Transformer		Z=25 Ω C=10pF
Current Transformer		Z=72 Ω C=10 pF
Transformer		C1=1.4nF R=12.1 Ω L=29.9mH C2=0.75nF
GIS Bus section		95 Ω

Disconnector during arcing		R0= 1012 Ω Rf =0.5 Ω T=0.6.10-9 s
SF6 to oil bushing		Z=126Ω C=14pF
SF6 to Air bushing		Z=95 Ω

3. RESULTS

The simulation is carried out using EMTP-ATP software. Integral time step for the simulation is taken as 0.1nanosecond as this value must be ten times less than the propagation velocity of shortest bus length for the considered GIS system. All switching operations are performed when the power frequency voltage is at its peak. To analyse the influence of switching conditions on VFTOs, three switching operations are simulated & VFTOs are estimated at different locations within GIS. System peak voltage per phase is given by Um=420kV*($\sqrt{2}/\sqrt{3}$) = 342.9kV,base voltage for Per unit value calculation is considered as 342.9kV.

Different Modes of Operation:

Influence of switching conditions on VFTOs and VFTCs [4].

Mode 1: - closing operation of disconnector DS3 associated with linefeeder1, when CB1 is open.

Mode 2: - closing operation of disconnector in bus link.

Mode 3: - closing operation of disconnector DS9 associated with transformer feeder, when CB3 is open.

From Fig.2, it can be observed that, During Line feeder switching the magnitude of VFTO gradually increases from the switching location until it encounters an open circuit breaker. Once the open circuit breaker is encountered, the VFTO values gradually decreases from this point. The VFTO magnitude again increases along the nodes and reaches the highest magnitude at GIS to Air bushing. Mode 1is producing the highest transient over voltage out of all the three cases and the magnitude is 3.79p.u,this is observed at GIS to Air Bushing interface since this location experiences most severe voltage stress because of more travelling wave reflections. PT1 and CT1 are also experienced higher transient voltages of 3.55 p.u. and 3.51 p.u, respectively. Even higher magnitudes of transient currents is observed in Mode 1 at 1.5 meters from the operating disconnector , In all the three modes, VFTCs are maximum near the disconnector and it gradually decreases as the distance from the operating disconnector is increasing. From table.2 maximum transient current is observed at DS3 with a magnitude of 15.6kA and GIS bus link is also carrying 14.2kA, which indicates significant current circulation with in the GIS structure. Mode 1 is indicating most severe switching condition in terms of voltage and current stresses.

In mode2, maximum value of VFTO is 3.29 per unit, which occurs at PT 1 (potential transformer in inefeeder1). Followed closely by 3.21 p.u. at CT1 and 3.20 p.u. at the GIS-Air Bushing compared to mode1 the transient over voltages are reduced approximately by 13%. The highest transient current in this case is observed as 13.9 kA located at 1.5m from the operating disconnector DS4,bus link is carrying a current of 10.8kA.Mode 3 is the switching condition in transformer feeder and in this case maximum value of VFTO (3.06p.u) occurs at transformer-oil bushing. This maximum value can be due to capacitive grading system of the bushing. Peak values of VFTO are in the range of 2 per unit to 3 per unit. Least transient over voltages are observed in mode3. PT1, CT1 and GIS-Air Bushing experiences noticable reductions in transient overvoltage magnitudes compared with Modes 1 and 2.Transient current distribution also changes considerably. The Bus Link current decreases sharply to 0.546 kA, indicating effective reduction of switching current through the bus. However, the current measured 1.5 m from the operating disconnector remains high (14.6 kA), demonstrating that travelling-wave current still exists locally even though voltages are substantially reduced.DS3 and DS4 experience very small voltages (0.08 p.u. and 0.12 p.u., respectively), indicating that these disconnectors are effectively isolated during this operating mode.Voltage transformers (PTs) and current transformers (CTs) consistently experienced higher transient voltages than most switching devices, suggesting these components require particular attention in insulation coordination studies.

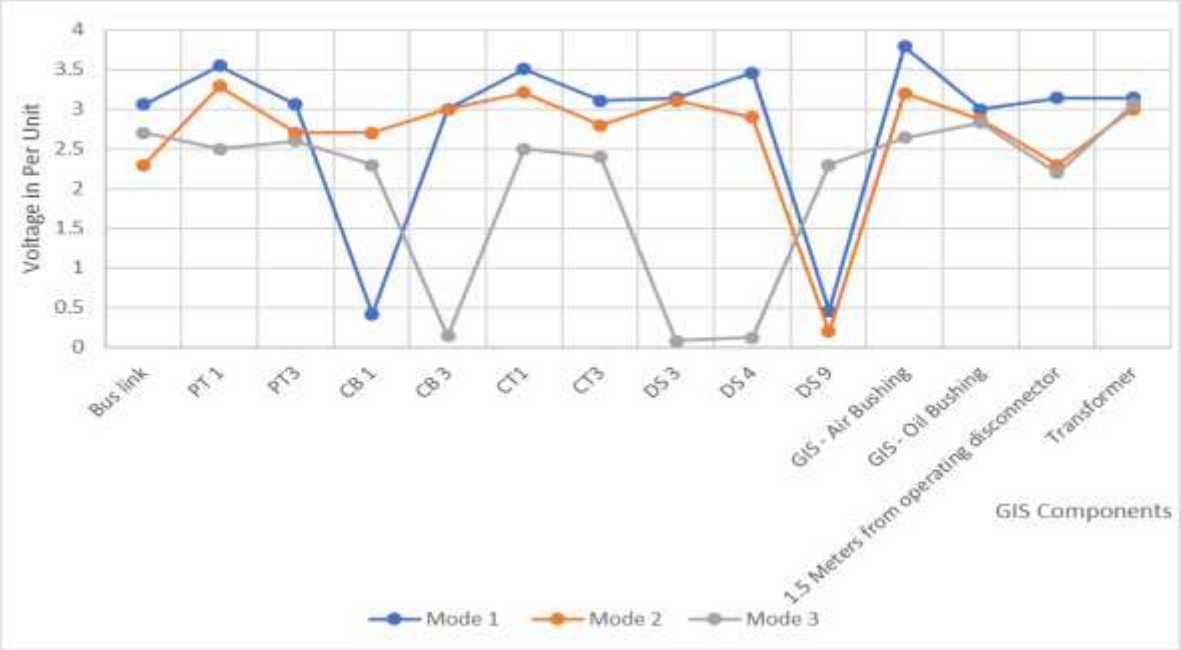


Fig2. Peak values of VFTOs for various modes of operation

Table.2. VFTOs & VFTCs at different locations for various modes of operation

S. No:-	GIS Component	Mode 1		Mode 2		Mode 3	
		voltage (p.u)	current (kA)	Voltage (p.u)	Current (kA)	Voltage (p.u)	Current(kA)
1	Bus link	3.06	14.2	2.3	10.8	2.7	0.546
2	PT 1	3.55	-	3.29	-	2.5	-
3	PT 3	3.06	-	2.7	-	2.6	-
4	CB 1	0.42	0.315	2.7	8.1	2.3	6
5	CB 3	3	-	3	-	0.14	-
6	CT 1	3.51	-	3.21	-	2.5	-
7	CT 3	3.11	-	2.8	-	2.4	-
8	DS 3	3.14	15.6	3.11	0.625	0.08	0.411
9	DS-4	3.46	5	2.9	7.7	0.12	6
10	DS 9	0.46	-	0.2	-	2.3	-
11	GIS to Air Bushing	3.79	8.2	3.2	-	2.64	2
12	GIS to Oil Bushing	3.003	-	2.87	-	2.83	-
13	1.5mts from operating disconnector	Line feeder 1		Bus link		Transformer feeder	
		3.14	15.6	2.3	13.9	2.2	14.6
14	Transformer	3.14	1.2*10-12	3.003	4.06*10-12	3.06	4*10-12

EFFECT OF TRAPPED CHARGE:

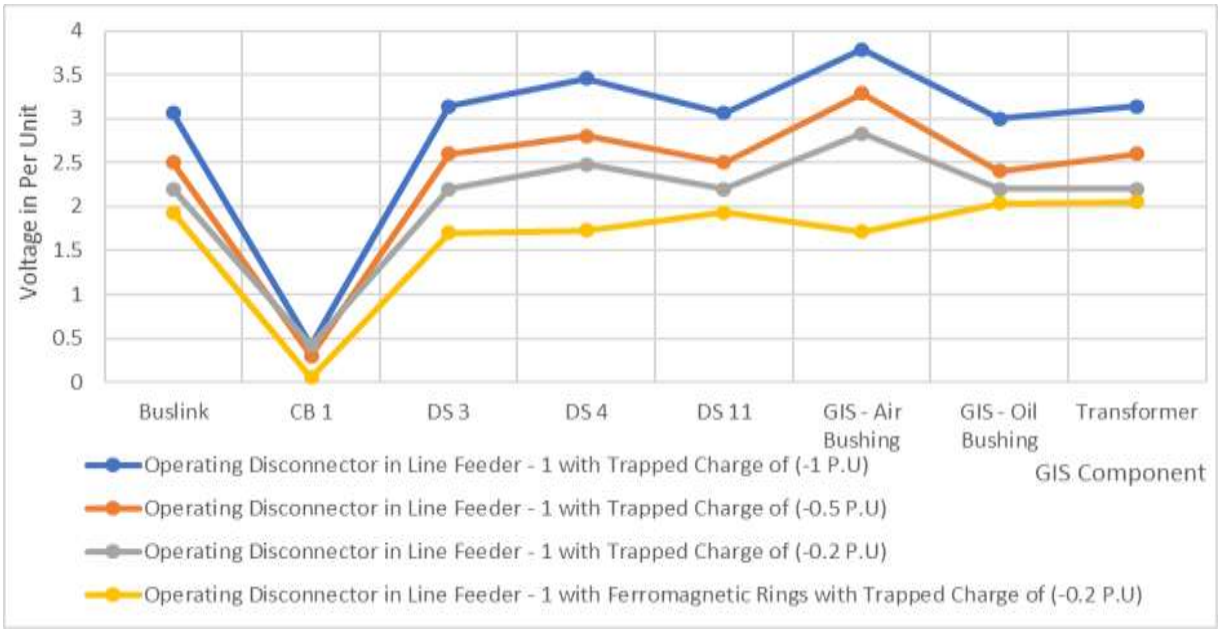


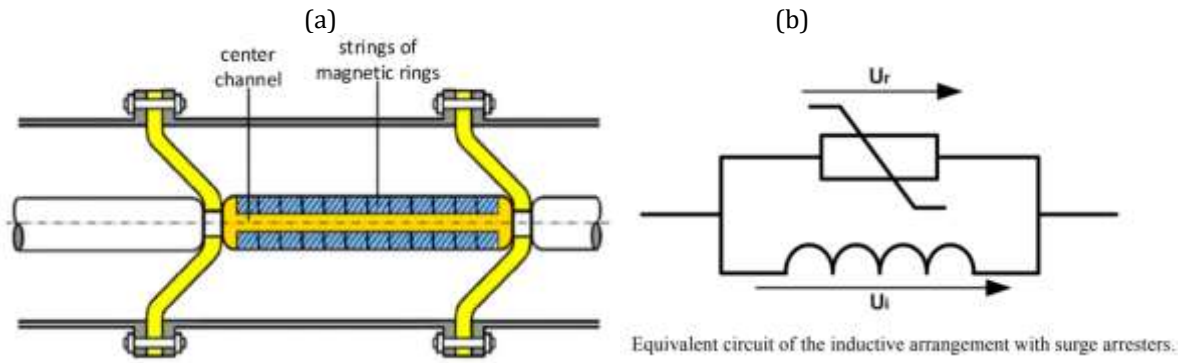
Fig3. Peak values of VFTOs at various locations in GIS

Fig 3 represents the transient over voltages and currents observed at various GIS components for four operating conditions operation of the disconnector in Line Feeder-1 with trapped charges of −1.0 p.u., −0.5 p.u., and −0.2 p.u., and operation with a −0.2 p.u. trapped charge combined with ferromagnetic rings. The results indicate that the trapped charge remaining on the isolated section has a significant influence on both transient overvoltage and current magnitude. As the trapped charge reduces from −1.0 p.u. to −0.2 p.u., a substantial reduction in switching stresses is observed throughout the GIS. For the Bus Link, the transient voltage decreases from 3.06 p.u. to 2.20 p.u., representing a reduction of approximately 28.1%, while the switching current decreases from 14.2 kA to 8.5 kA, corresponding to a reduction of nearly 40.1%. Similar trends are observed at DS3, where the voltage reduces from 3.14 p.u. to 2.20 p.u. and the current decreases from 15.6 kA to 9.3 kA. These reductions confirm that lower trapped charge substantially decreases the energy available for transient oscillations.

GIS-to-Air Bushing experiences the highest transient overvoltage under all operating conditions due to travelling-wave reflections at the GIS-air interface. Peak of VFTO decreases from 3.79 p.u. for −1.0 p.u. trapped charge to 2.83 p.u. for −0.2 p.u., while the corresponding current reduces from 8.2 kA to 4.8 kA. This represents reductions of approximately 25.3% in voltage and 41.5% in current. connection of ferromagnetic rings together with a −0.2 p.u. trapped charge provides the greatest mitigation of switching transients. The Bus Link voltage further decreases to 1.93 p.u , while the current falls to 4.7 kA. Likewise, the GIS-to-Air Bushing voltage reduces to 1.71 p.u , corresponding to an overall reduction of approximately 54.9% compared with the original −1.0 p.u. trapped-charge case. The current at the same location decreases to 3.03 kA, representing a reduction of approximately 63.0%.

C. FERROMAGNETIC RINGS (WITH TRAPPED CHARGE -0.2 P.U):

Ferromagnetic ring (Fig.4.(a)) is a high frequency magnetic material having nonlinear characteristics is one of the mitigation methods to suppress VFTO. Ferrite rings are placed around GIS bus duct. These rings can absorb the transient energy whenever there is prestrike or restrike which occurs during the switching operation of disconnector. The equivalent model of ferrite rings can be simplified as parallel combination of resistor (70Ω) and inductor (0.02H). Circuit based model of ferrite rings is shown in Figure 4(b).



Equivalent circuit of the inductive arrangement with surge arresters.

Fig.4. Ferro magnetic rings connection with GIS busbar (a) Physical model (b) Equivalent circuit

It is observed that by using ferrite rings the VFTO magnitude is reduced to a significant level as seen from the graph. The main drawback of this method is that as VFTOs have high magnitudes and frequency, the ferrite rings may get saturated. It was also observed that the magnitude of VFTC increases with increase in trapped charge as presented in table. However, by using ferromagnetic rings, considering (-0.2 p.u) trapped charge, low magnitudes of VFTC are observed. At DS, the voltage decreases to 1.70 p.u, while the current reduces dramatically from 15.6 kA to 4.3 kA, corresponding to reductions of 45.9% and 72.4%, respectively. Similar improvements are observed at DS4 and DS11, indicating that the mitigation technique is effective throughout the GIS. The transformer terminal also experiences reduced transient voltage, decreasing from 3.14 p.u. to 2.05 p.u. Although the associated transient current remains extremely small because of the transformer's high impedance at high frequencies, the reduction in voltage contributes to improved insulation reliability. Overall, the results demonstrate that reducing trapped charge alone significantly reduces switching over voltages and currents, while the addition of ferromagnetic rings provides an additional damping effect by suppressing high-frequency oscillations and reducing travelling-wave reflections. Consequently, the combined mitigation strategy achieves the lowest transient stresses across all monitored GIS components and represents the most effective operating condition among the cases investigated.The waveforms below shows the VFTO at GIS - Air bushing for operating the disconnector in line feeder 1 with a trapped charge of 0.2 p.u.

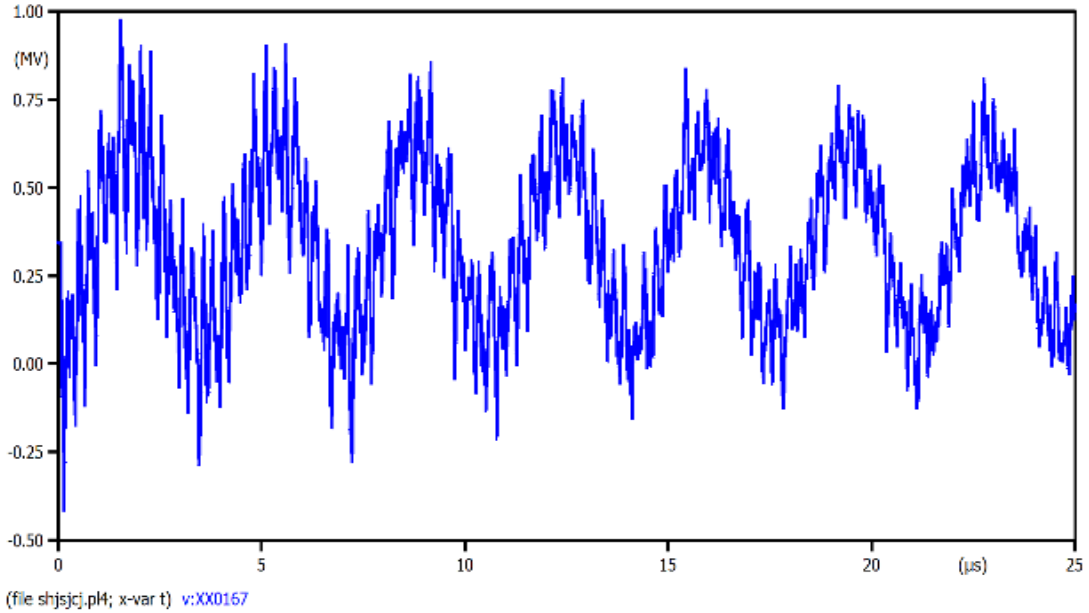


Fig 5.VFTO wave form at GIS-Air bushing for operating the disconnector in line feeder 1(with -0.2 p. u trapped charge)

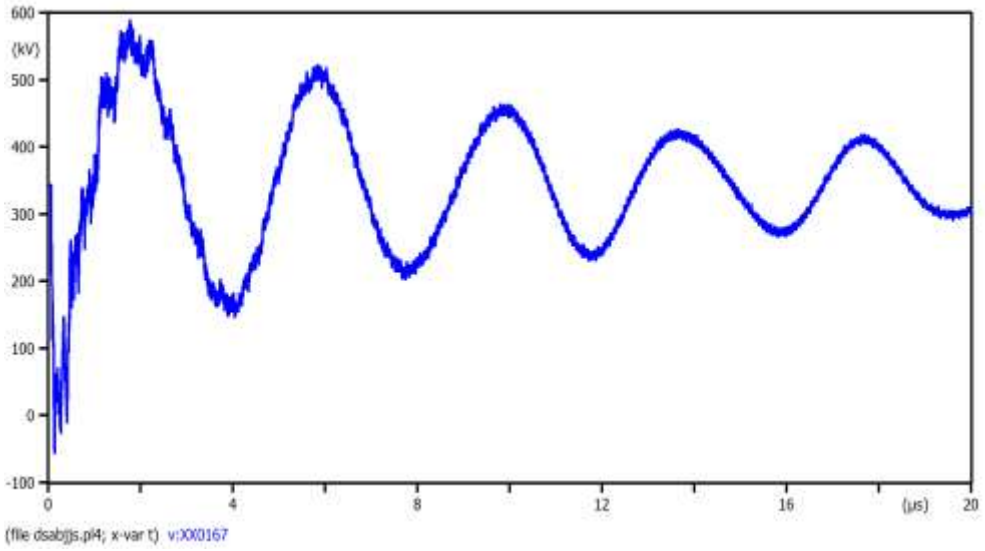


Fig 6 .VFTO wave form at GIS-Air bushing for operating the disconnector in line feeder 1(with -0.2 p. u

trapped charge) after incorporating ferrite rings

Fig 5. shows the waveform of VFTO at GIS-Air bushing for operating the disconnector in line feeder 1(with -0.2 p. u trapped charge).Its Peak Value is 974 kV. Fig 6. shows the waveform of VFTO at GIS-Air bushing for operating the disconnector in linfeeder1 after connecting ferro magnetic rings (-0.2 p. u trapped charge),its Peak value is reduced to 588 kV and its steepness of VFTO waveform also reduced to the possible extent.

D. Effect on transients (VFTOs and VFTCs) for variation in length of different terminal components connected to GIS:

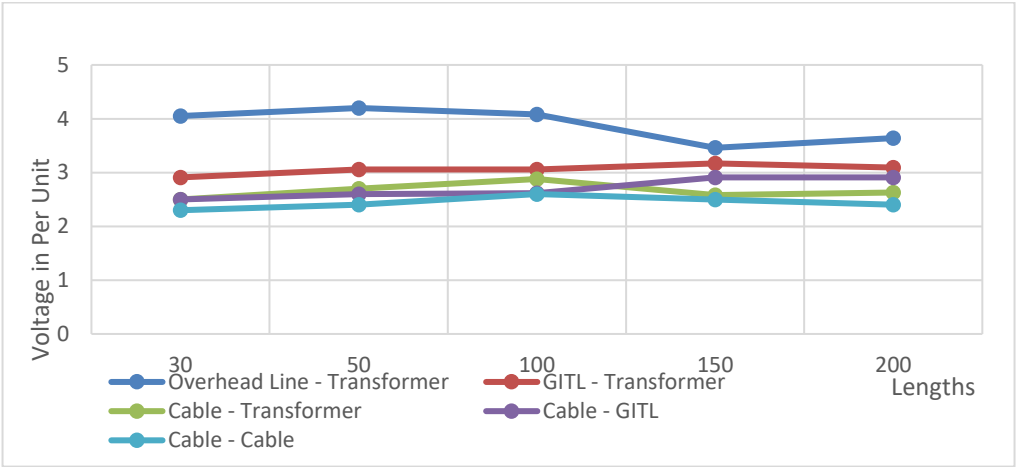


Fig7.VFTO magnitudes at GIS-Air bushing due to change in length of terminal components

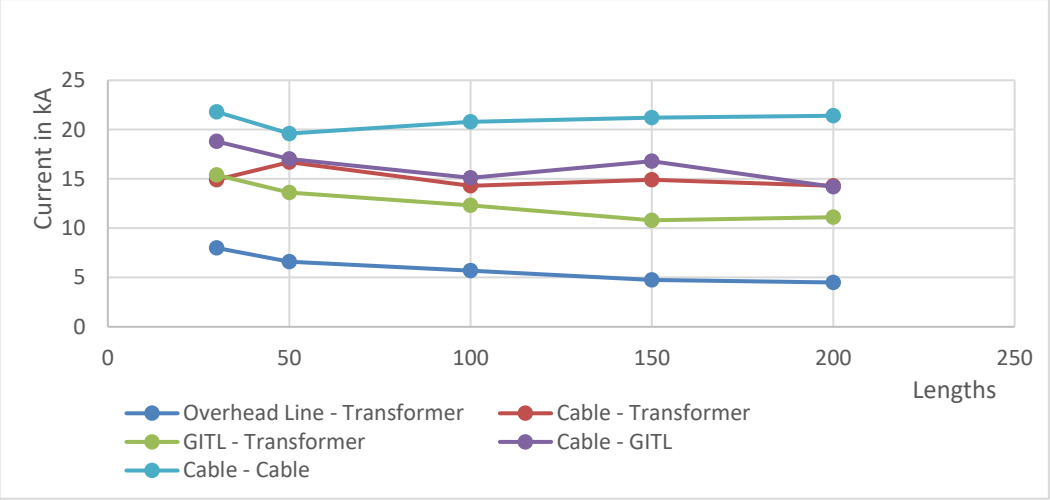


Fig.8. VFTCs at GIS - Air Bushing for different configuration with varying lengths

From Fig.7. It is observed reduction in peak magnitude of VFTO is more for cable-cable configuration and is less overhead line transformer configuration. It is observed from Fig.8 that reduction in VFTC is high for overhead line (source side) -Transformer (load side) configuration and it is low for cable (source side) -cable (load side) configuration. Hence it can be concluded that VFTC magnitude can be reduced if overhead line (source side) -Transformer (load side) configuration is used.

In fig 9 the VFTO waveform at GIS to air bushing is shown for terminal components of overhead line and cable at the source end and ferrite rings, it is observed that VFTO magnitude is reduced with insertion of ferrite rings near to the operating disconnector. From the wave form it was observed that VFTO magnitude.

"Fast Fourier Transform (FFT) analysis reveals that the dominant frequency components range between 1 MHz and 70 MHz. These high-frequency Very Fast Transient Over voltages (VFTO) are directly caused by the short, one-meter bus section connecting the operating disconnector to the main busbar. As surges travel along this brief span, they encounter a 'T' junction, causing a portion of the wave to reflect while the rest transmits to the main busbar. The transmission coefficient at this junction, where the GIS bays meet the main busbar is calculated using the following equation

$$T = \frac{\frac{2}{Z_1}}{\frac{1}{Z_1}+\frac{1}{Z_2}+\frac{1}{Z_3}} \quad (3)$$

Where Z1 is the characteristic impedance of the bus section through which the incident surge is coming, Z2 and Z3 are the characteristic impedance of the remaining two bus sections at the 'T' junction. Since all the

characteristic impedance values are the same, the transmission coefficient will be 2/3. So, the reflection coefficient at 'T' junction becomes -1/3.

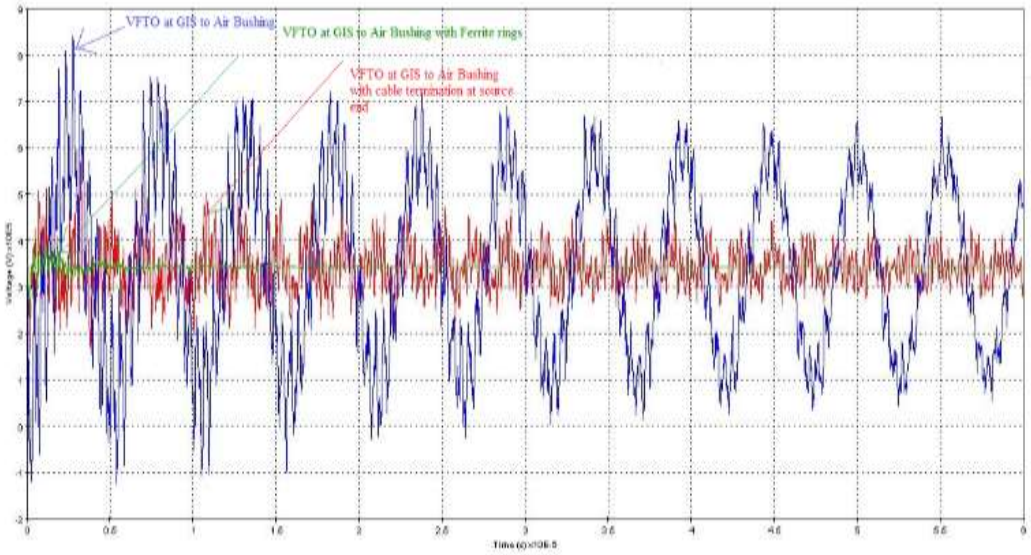


Fig.8. Super imposed Wave form of the VFTO with source side overhead line, cable, with ferrite rings

E. Estimation of Electromagnetic field associated with VFTCs:

The VFTCs generated in GIS have electromagnetic fields associated with them. In this study the E-field and H-field are estimated by developing a 3-D model of GIS bus duct using COMSOL multi physics software.

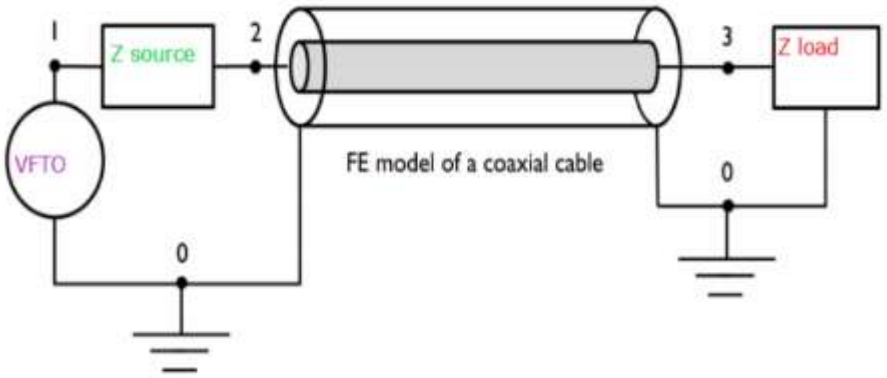
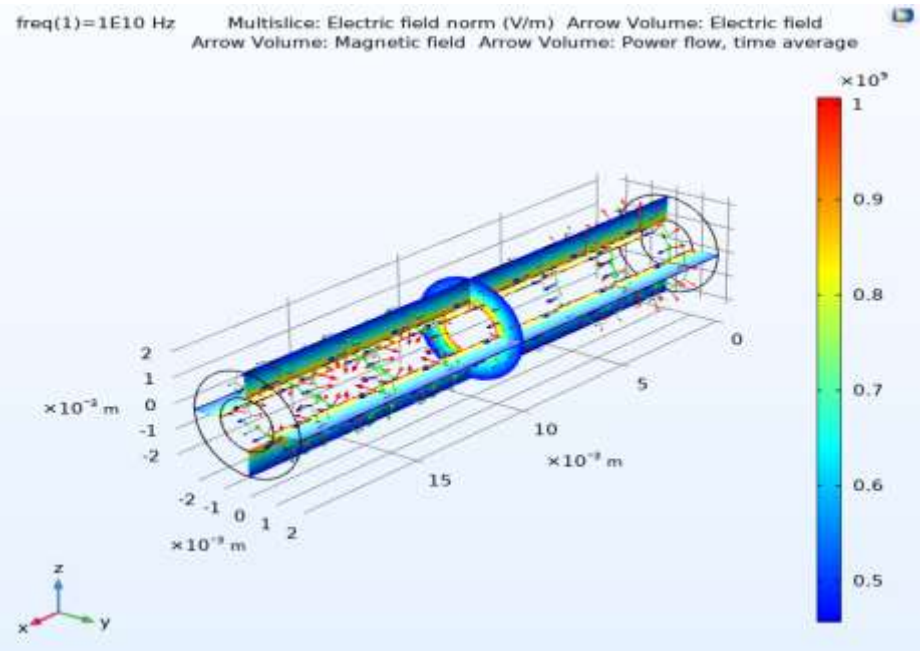


Fig.9. Schematic of a section of a coaxial GIS structure connected to a transient voltage source, source impedance, and load.

The figure 9 shows a coaxial cable which is connected to a transient voltage source, with matched impedance of both source and load. Fig9. Electric field norm and magnetic field, and power flow (green, blue arrows) inside the coaxial cable.

At the two ends of this coaxial cable, lumped port boundary conditions are used to connect nodes 0-2 and 0-3 respectively on either side of the model. The path along the cable have some field and the path integral of this electric field along cable length is nothing but voltage. So, we chose two arbitrary points in the designed model and field can be estimated from it. This field and power flow plot shows TEMF wave propagation inside coaxial cable which is excited by VFTO magnitude of 1300kV obtained from circuit based simulation using EMTP -ATP.



Conclusion

The paper investigates Very Fast Transient Overvoltages (VFTOs) and Very Fast Transient Currents (VFTCs) in a 420 kV Gas Insulated Switchgear (GIS) system modeled in EMTP-ATP using equivalent circuit models. VFTOs and VFTCs at different locations in the GIS are analyzed by operating the disconnector under three different switching modes. The peak values of VFTOs and VFTCs are evaluated for all three modes. It is observed that the peak VFTO values generally lie in the range of 2 to 3 p.u., while the VFTC is maximum at the operating disconnector and gradually decreases as the distance from the operating disconnector increases.

The effect of trapped charge on VFTO and VFTC is also investigated by considering trapped charges of −1 p.u., −0.5 p.u., and −0.2 p.u. The results indicate that both VFTO and VFTC magnitudes increase with an increase in the magnitude of trapped charge. For the worst-case trapped charge of −1 p.u., the VFTO peak at the disconnector increases from 1.38 p.u. to 1.82 p.u. The maximum VFTO among the different measuring locations is observed at VT1 for the considered switching conditions, reaching 2.09 p.u. for −1 p.u. trapped charge. The high-frequency energy associated with these transients can impose additional stress on GIS insulation and may contribute to insulation-related problems. The highest frequency component of the VFT is observed at the disconnector terminal and is approximately 68 MHz, whereas at the transformer and reactor terminals, the presence of high capacitance limits the frequency components to below 10 MHz. To mitigate the effects of VFTO and VFTC, ferromagnetic rings are investigated for the case of −0.2 p.u. trapped charge. It is observed that the use of ferromagnetic rings significantly reduces the magnitude of the transients. However, the paper also discusses the major drawback associated with the practical application of ferromagnetic rings. In addition, the influence of different terminal-component configurations on VFTO and VFTC is studied. Among the configurations considered, the highest VFTO of 3.67 p.u. is observed at the transformer for the overhead-line source-side and GITL load-side configuration, whereas the lowest VFTO of 0.18 p.u. is observed at the circuit breaker for the cable source-side and GITL load-side configuration.

The effect of the lengths of the terminal components on the transients is also investigated. It is found that the reduction in VFTO is maximum for the cable source-side and cable load-side configuration, while the reduction in VFTC is maximum for the overhead-line source-side and transformer load-side configuration. Furthermore, the electromagnetic field associated with VFTC is evaluated using a three-dimensional coaxial-cable model developed in COMSOL. Overall, the study demonstrates that trapped charge, disconnector switching, terminal configuration, and terminal-component lengths have a significant influence on VFTO and VFTC in high-voltage GIS, while suitable mitigation techniques such as ferromagnetic rings can effectively reduce the magnitude of these transients.

References

1. H. J. Koch (Editor), Gas Insulated Substations, Wiley-IEEE Press, 2022
2. J. Meppelink, K. J. Diederich, K. Feser and W. R. Pfaff, “Very fast transients in GIS,” IEEE Transactions on Power Delivery, vol. 4, no. 1, pp. 223-233, 1989.
3. A. Ametani, H. Xue, T. Ohno and H. Khalilnezhad, Electromagnetic Transients in Large HV Cable Networks: Modelling and calculations, IET Press, 2022.
4. U. Riechert and W. Holaus, “Ultra high-voltage gas-insulated switchgear – a

technology milestone," European Transactions on Electrical Power, vol. 22, pp. 60-82, 2012.
5. H. Xue, A. Ametani and J. Mahseredjian, "Very fast transients in a 500 kV gas-insulated substation," IEEE Transactions on Power Delivery, vol. 34, no. 2, pp. 627-637, 2019.
6. A. Khamlichi, G. Donoso, F. Garnacho, G. Denche, A. Valero and F. Alvarez, "Improved cable connection to mitigate transient enclosure voltages in 220-kV gas-insulated substations," IEEE Transactions on Industry Applications, vol. 52, no. 1, pp. 562-569, 2016.
7. G. Carrara, L. Dellera and G. Sartorio, "Switching surges with very long fronts (above 1500 μs): effect of front shape on discharge voltage," IEEE Transactions on Power Apparatus and Systems, vol. PAS-89, no. 3, pp. 453-456, 1970.
8. J. G. R. Filho, J. A. Teixeira Jr, M. R. Sans and M. L. B. Martinez, "Very fast transient overvoltage waveshapes in a 500-kV gas insulated switchgear setup," IEEE Electrical Insulation Magazine, vol. 32, no. 3, pp.17-23, 2016.
9. D. Moreira, M. Nunes, D. C. Moreira, D. Costa, "Analysis of VFTO during the failure of a 550-kV gas-insulated substation," Electric Power Systems Research, vol. 189, 2020
10. J. Zhao, W. Chen, K. Li, Z. Teng, N. Li, T. Wen and X. Fan, "Analysis of conducted disturbance via current transformer due to switch operation of GIS disconnector in UHV substation," CSEE Journal of Power and Energy Systems, vol. 9, no. 3, pp. 1227-1234, 2023.