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MODELING AND MITIGATION OF VERY FAST TRANSIENT OVER VOLTAGES (VFTOS) IN GAS-INSULATED SUBSTATIONS DUE TO SWITCHING OPERATIONS

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Abstract : This research addresses the intricacies of Very Fast Transient Over voltages (VFTOs) encountered during switching operations within Gas-Insulated Substations (GIS). VFTOs, characterized by swift and short-lived voltage fluctuations with amplitudes ranging from 1.2 to 3 per unit (pu) and frequencies in the megahertz (MHz) range, present significant challenges to GIS stability and reliability. Our investigation centers on comprehensive modeling and simulation techniques using lumped models. These models, though simplified, offer valuable insights into VFTO behavior within GIS components. Specifically, we explore VFTO occurrences at critical points, notably in proximity to the bushings. The significance of this research lies in its contribution to enhancing the understanding of VFTOs and developing effective mitigation strategies. Through this study, we strive to pave the way for improved reliability and operational integrity of high-voltage GIS systems, ensuring the continued functionality of essential power systems.

Keywords **- VFTOs, Gas-Insulated Substation, Modeling, Mitigation, Switching Operations.**

I. INTRODUCTION

In this research, we explore Very Fast Transient over voltages (VFTOs) that occur during critical switching operations within a Gas-Insulated Substation (GIS). These sudden electrical events can impact GIS system stability and reliability. Our objective is to study their behaviour using simplified lumped models and investigate practical ways to mitigate their effects. VFTOs are characterized by rapid and brief voltage changes, typically ranging from 1.2 to 3 pu, and they occur at frequencies measured in megahertz (MHz). They have long fascinated professionals in high-voltage substations. VFTOs happen when the GIS switches, and these swift voltage fluctuations can potentially damage the insulation of essential substation components. To better understand and address VFTOs, we employ advanced modeling techniques to examine their occurrence within the GIS.

Numerous studies have contributed to understanding Very Fast Transient Over voltages (VFTOs) in Gas-Insulated Substations (GIS). [1] Explored VFTOs in a 500 kV GIS, offering insights into their behaviour. [2] Provides a comprehensive resource on Gas Insulated Substations. The IEC Standard 60071-1 [3] defines GIS design principles. The CIGRE Working Group D1.03 [4] provides VFTO management guidelines. [5] Investigates VFTO characteristics with hybrid reactive power compensation. [6] Studies VFTO interference on secondary cables in GIS substations. [7] Models VFTOs in a 400 kV GIS. [8] Evaluates VFTOs in a 500-kV GIS power substation. [9] Offers modelling and analysis guidelines for VFTOs. [10] Explores VFTOs and mitigation techniques in gas-insulated substations. This body of work forms the basis for our research on VFTO mitigation strategies within GIS.

In line with recent research and industry standards, our work aims to enhance the understanding of Very Fast Transient over voltages (VFTOs) in a 500 kV Gas-Insulated Substation (GIS) during switching operations. Drawing insights from relevant studies, our goal is to contribute to the field of VFTO mitigation in GIS. This paper presents our findings, methodologies, and mitigation strategies, with the aim of improving the reliability of high-voltage GIS systems.

II. MODELING OF GAS INSULATED SUBSTATION:

To investigate the behaviour of a 500 kV gas-insulated substation (GIS) during switching operations, we developed a simplified model with a primary focus on key components: bushings, isolated switches, circuit breaker, and enclosure filled with SF_6 gas.

Component Configuration:

1. Bushing and Isolated Switch: The model begins with a bushing followed by an isolated switch, representing the connection to the external power system.
2. Circuit Breaker: A circuit breaker, which is approximately 2 meters long, is placed in series with the circuit for switching operations.
3. Isolated Switch: Another isolated switch is incorporated in the model.
4. Bus Bar: The primary component of interest is the gas-insulated bus bar, with a radius of 12.5 cm and a length of 1 meter.
5. Enclosure: All components are enclosed within an outer casing with a radius of 46 cm, representing the GIS enclosure.

Parameters (for 1-meter Bus Bar Segment):

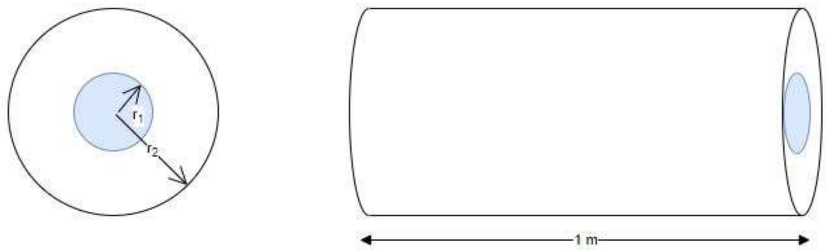


Figure 1: Cross section of GIB: core-12.5 cm, pipe-46 cm

- **Capacitance**

$$C = \frac{2\pi \in_o \in_r}{\ln r_2 / r_1}$$

$C = (2\pi * 8.873 \times 10^{-12}$ F/m / ln(0.46/0.125)) * 1

$C = 42.789 \times 10^{-12}$ F

= 42.789 pF

Calculated as approximately 42.789 pF for the 1-meter gas-insulated bus bar segment.

- **Inductance**

$$L = \frac{\mu \ln r_2 / r_1}{2\pi}$$

$L = ((4\pi \times 10^{-7}$ H/m) / (2π)) * ln (0.46/0.125) * 1

$L \approx 2.6058 \times 10^{-7}$ H

Estimated to be approximately 2.6058×10^{-7} H for the 1-meter bus bar segment.

- **Surge Impedance**

$$Z_0 = \sqrt{L / C}$$

$Z = \sqrt{((2.6058 \times 10^{-7} \text{ H}) / (42.789 \times 10^{-12} \text{ F}))}$

$Z \approx 78\ \Omega$

Approximately 78 Ω, representing the surge impedance for the 1-meter bus bar segment.

- Propagation Velocity (v): approximately 263.664 m/μs for VFTs within the 1-meter gas-insulated bus bar segment.

Table 1: Effective equivalent parameters of electrical appliance

Key equipment	Circuit parameter
Power Transformer	C_T = 9000 pF L = 20 mH
Lightning Arrester	C_{MOA} = 19 pF
Bushing	C_{BS} = 300 pF
Grounding Switch	C_{ES} = 240 pF
Circuit Breaker	C_B = 410 pF
Isolating Switch	C_{DS}= 150 pF
Surge Impedance	Z = 78 Ω
Propagation Velocity (v)	V = 263.664 m/μs

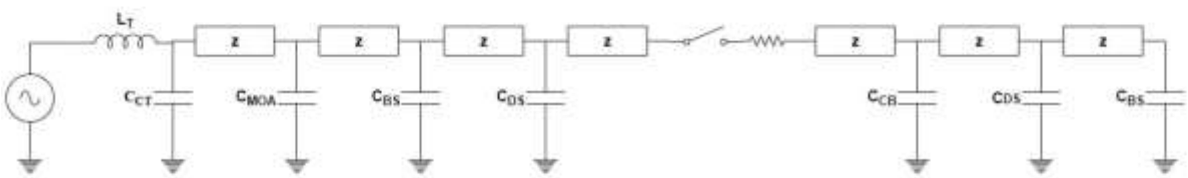


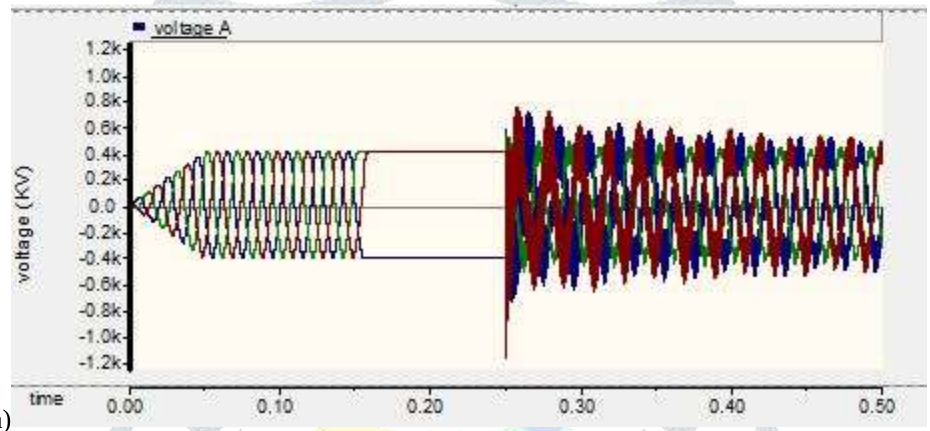
Figure 2: Typical VFTO circuit type model

III. Results and Discussions

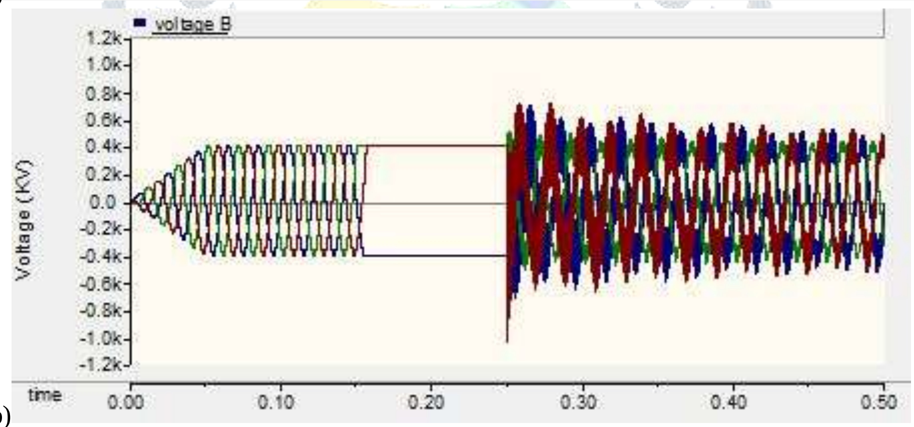
It was evident that the highest voltage peaks (2.88 pu), as revealed by the simulation, occurred specifically at the bushings within the 500 kV Gas-Insulated Substation (GIS). Notably, these peak voltage values were observed to be the most pronounced among all critical points, underscoring the critical vulnerability of these components to Very Fast Transient Over voltages (VFTOs). Additionally, waveform analysis identified high-frequency components in the megahertz range, characteristic of VFTOs. These findings, with specific voltage values and their locations, emphasize the need for robust insulation and protective measures at the bushings to mitigate potential damage. Furthermore, the presence of high-frequency content highlights the importance of thorough insulation design and raises questions about the potential benefits of component suspension to enhance GIS performance and reliability in the presence of VFTOs.

Table 2: Peak magnitude of VFTOS

Position	Peak voltage V_P	V_P in pu
Point A	- 1177 KV	2.88
Point B	- 1027 KV	2.51
Point C	- 940 KV	2.30
Point D	- 814 KV	1.99
Point E	- 880 KV	2.15
Point F	- 1015 KV	2.48



a)



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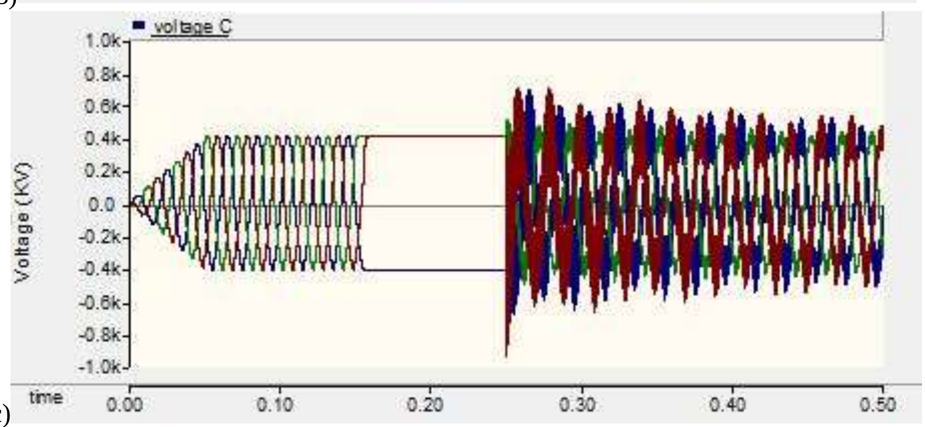

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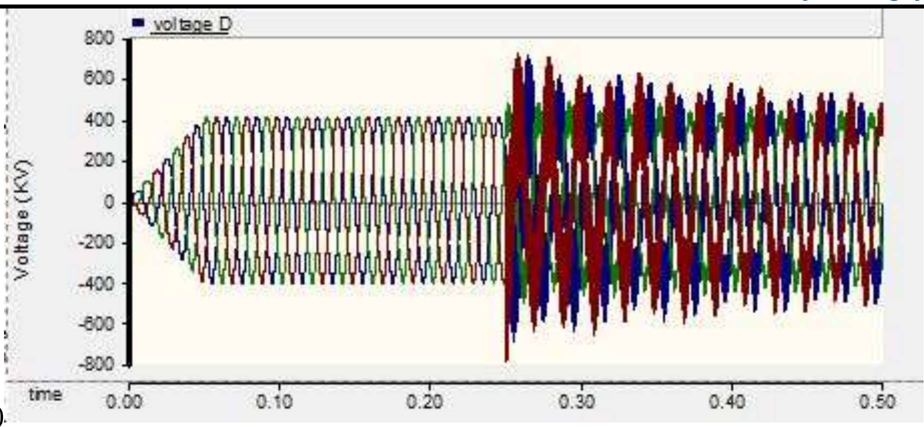

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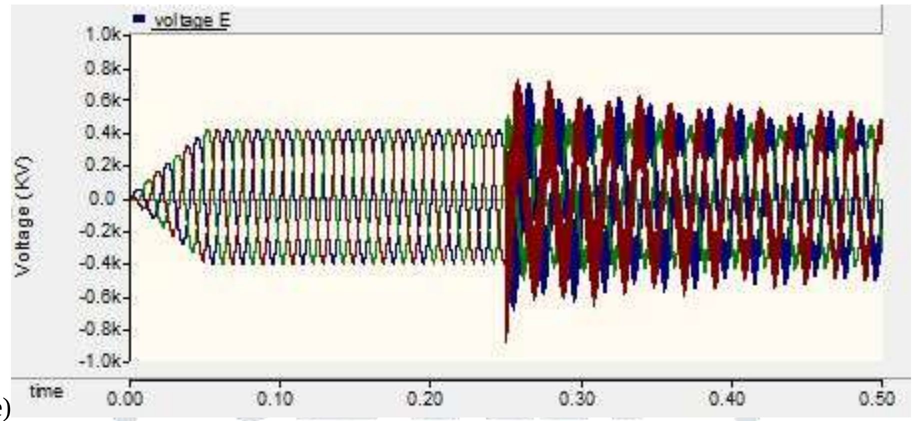

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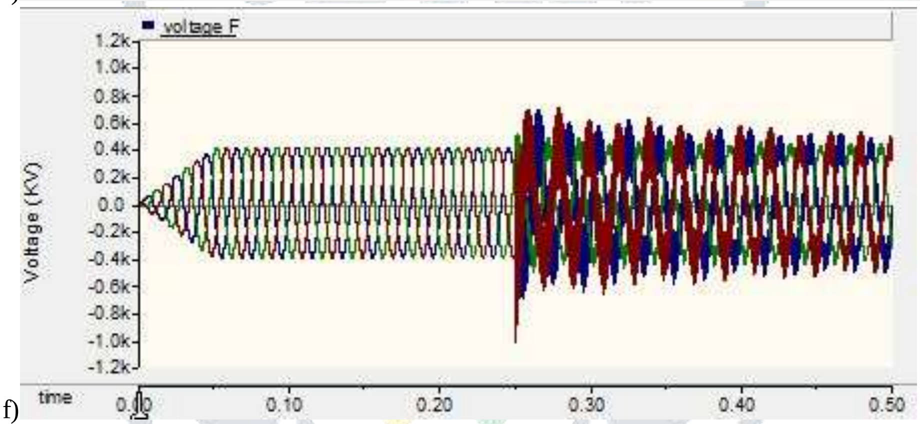


f)

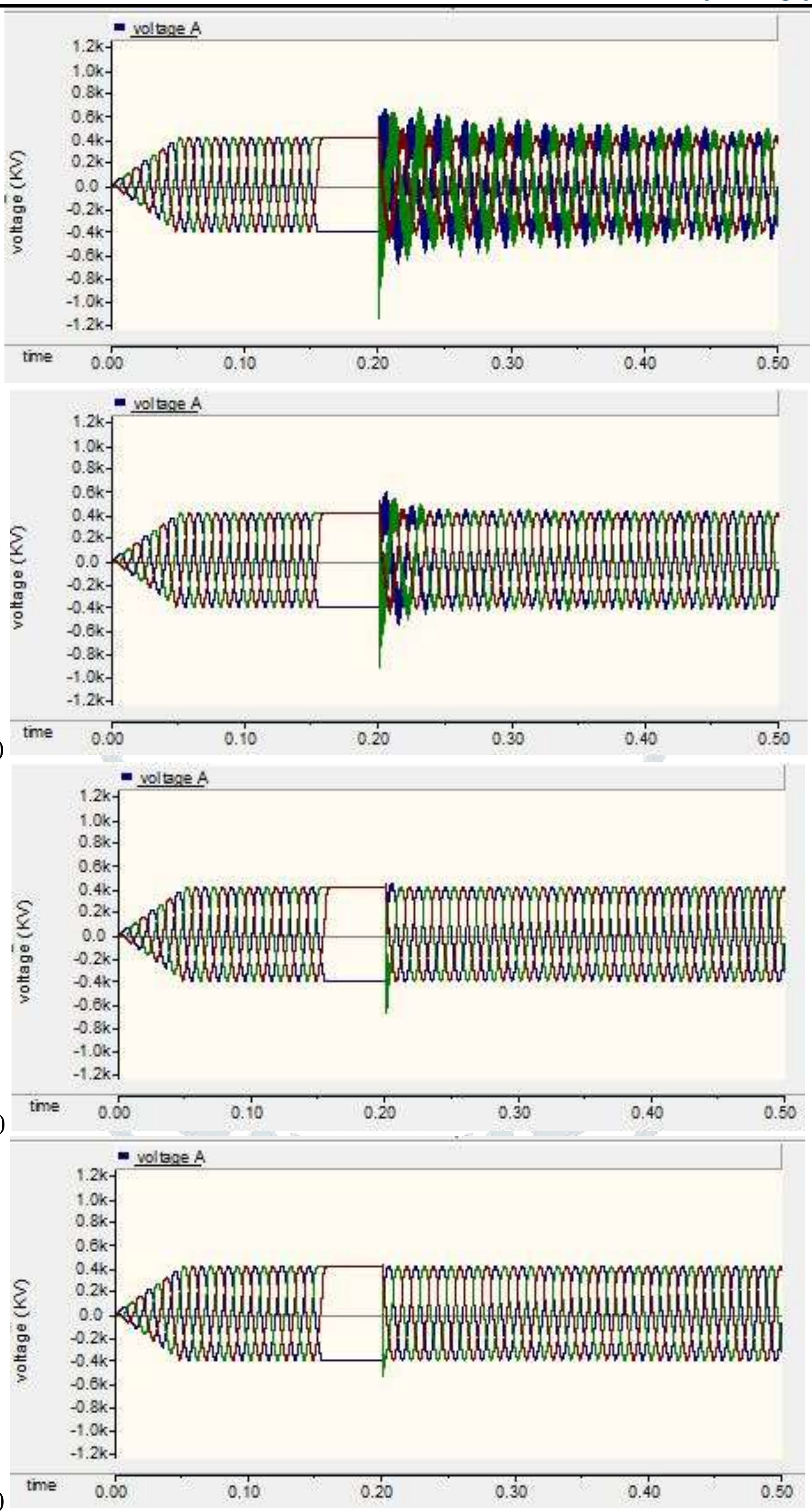
Figure 3: VFTO waveforms at various positions in GIS

IV. MITIGATION TECHNIQUES OF VFTOS

Damping resistors: Shunt/ damping resistors are pivotal in mitigating Very Fast Transient Over voltages (VFTOs) within the 500 kV Gas-Insulated Substation (GIS). These resistors, connected in parallel before switch closures, provide an alternative path for transient energy during switching operations. Constructed with high-resistance materials, equipped with heat dissipation systems and protective enclosures, they play a critical role in safeguarding GIS components. In our simulations, the effectiveness of shunt damping resistors with varying resistance values was explored. Notably, a 500 Ω resistor demonstrated the most substantial reduction in VFTOs, lowering peak voltage (VP) to 1.27 pu. This underscores the pivotal role of shunt damping resistors in reducing the impact of VFTOs, making them a valuable asset in enhancing GIS system reliability during switching operations.

Table 3: Peak Voltages at point A

Resistances	1 Ω	10 Ω	100 Ω	500 Ω
Peak Voltages V_P	2.86 pu	2.26 pu	1.65 pu	1.27 pu



a) b) c) d)

Figure 4: voltage waveforms at Point A for different values of damping resistor a) r = 1 Ω, b) r = 10 Ω, c) r = 100 Ω, d) r = 500 Ω

Ferrite rings: The equivalent circuit of Ferrite rings typically consists of a parallel connection of a resistor and an inductor. In our specific case, the parameters of these Ferrite rings were configured as follows: a resistance (R) of 78 Ω, taken same as the surge impedance (Zs), and an inductance (L) of 0.02 mH. To gauge their effectiveness, ten Ferrite rings were incorporated into the simulation. The results were indicative of the substantial VFTO reduction achieved, with the peak voltage (VP) decreasing from 1177 kV to 1050 kV. This significant attenuation in transient over voltages underscores the instrumental role that Ferrite rings play in enhancing the reliability and performance of the GIS system during switching operations.

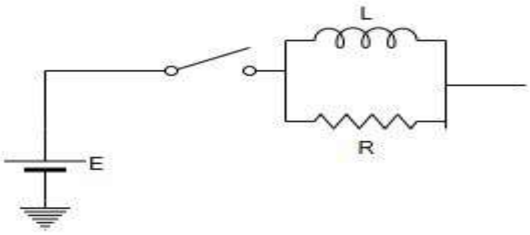
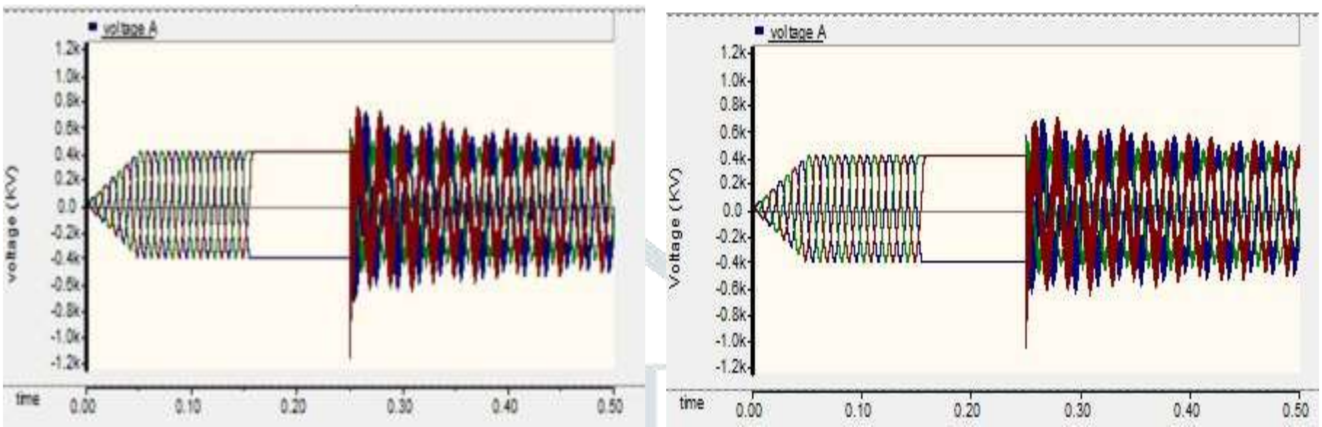


Figure 5: Equivalent circuit of the ferromagnetic ring



a) Vp : - 1177 KV b) Vp: - 1050KV

Figure 6: a) Wave form without Ferrite rings b) Wave form with Ferrite rings

V. CONCLUSION:

In this study, we embarked on a comprehensive exploration of Very Fast Transient Over voltages (VFTOs) within the context of a 500 kV Gas-Insulated Substation (GIS). We initiated our journey by delving into the modeling of GIS components, meticulously simulating the intricate interplay of switching operations. This endeavour unveiled the profound vulnerability of certain critical points within the GIS, with bushings emerging as the most susceptible to VFTOs, notably experiencing the highest peak voltages.

Further, our investigation extended to mitigation techniques, where we scrutinized the efficacy of damping resistors and Ferrite rings. Damping resistors strategically placed in parallel before switch closures, demonstrated remarkable potential. Higher resistance values, such as 500 ohms, yielded substantial VFTO reductions, reaffirming their importance in enhancing GIS system reliability during switching operations. Equally instrumental were the Ferrite rings, characterized by their parallel resistor-inductor equivalent circuit. In our simulation, the deployment of ten Ferrite rings led to a notable reduction in peak voltage, from 1177 kV to 1050 kV, attesting to their pivotal role in mitigating VFTOs.

In summation, our study underscores the critical significance of safeguarding GIS systems against VFTOs, especially at vulnerable points like bushings. The adoption of shunt damping resistors and Ferrite rings emerges as a practical and effective strategy to fortify GIS resilience during switching events.

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