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Suppression Techniques of VFTOs generated by Switching Operations in UHV 1200KV GIS Substation

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Abstract: In this paper, four distinct suppression techniques are used to minimize VFTOs in 1200KV UHV GIS substations. Restrike and prestrike events that occur during switching operations in a disconnector switch can lead to increased arcing currents and the generation of traveling waves. These high-frequency transients can decrease the dielectric strength of elements in the substation. The maximum value, frequency, and quantity of incidents between disconnector opening or closing operations are mainly caused by the development of VFTOs. The frequency operation of VFTOs is associated with the time taken for voltage collapse in sulfur hexafluoride gas and the movement of traveling waves within Gas Insulated Switchgear. To reduce VFTOs in a 1200KV UHV substation, four methods are proposed, and results are presented in periods of peak value, rise time, as well as settling period of oscillations. Simulations were performed on a 1200KV substation using MATLAB/SIMULINK.

1. Introduction

In electrical power transmission systems Gas Insulated Switchgear require less amount of space compared to Air Insulated Switchgear and hence treated as a extremely reliable addition to existing systems [1]. Sulfur Hexafluoride is the insulation medium which can be used in GIS substation. Even the cost of switchgear insulated with SF6 is high, compared to requirement of space and maintenance, this increased price can be justified to shift to GIS base substations. Influence of moisture, pollution, dust etc. is very much less on GIS substations. Arc quenching capacity of SF6 is 10 times better than air, and insulating ability is also two to three times better Formation of VFTOs is caused by disconnector operations that result in the shifting of tiny capacitive currents expected to repeated restriking of the disconnector contacts. The disconnector operates at a slower rate than a circuit breaker, resulting in a maximum overvoltage of 3 per unit (3 p.u.).

Vacuum Fault Interrupters with elevated amount and sharpness are created by the expression and combination of traveling waves within Gas Insulated Switchgear.Suppressing these VFTOs, though, is a persistent issue and numerous solutions have been proposed. One approach to reducing VFTOs is to avoid undesirable GIS layouts and hazardous operating procedures with disconnector switches, but this imposes significant limits on the strategy and management of the GIS [4]. The traveling wave nature of VFTOs requires modeling Gas Insulated Switchgear components are modelled as electrical equivalent circuits that incorporate both distributed parameters, such as surge impedance and traveling wave speed, and grouped sections. Reflection and bending of traveling waves occur when there is a change in surge impedance.

VFTOs can impact the reliable operation of GIS and harm the insulation of high-voltage equipment, particularly the windings of transformers. At the instant of generation of VFTO with abrupt rise in peak magnitude, causes irregular voltage distribution on the windings [6]. Currently, Vacuum Fault Interrupters play a crucial role in shaping the design of the dielectric component in Ultra-High Voltage (UHV) Gas Insulated Switchgear. A consistent and basic solution of VFTO mitigation is important to protect the other equipment of substation. Disconnector switches with series resistor for UHV GIS is proposed in [7]. But cost and maintenance of disconnector switches is more compared to conventional disconnector switches.

Various approaches for VFTO mitigation are examined in recent times by scholars. Mitigation of VFTOs in 245KV GIS shown in [8]. Utilizing High frequency resonators [9], magnetic material [10], capacitors [11] to suppress VFTOs described in literature. In VFTOs a novel magnetic material for suppression is presented in [12], the impact depends on the energy dissipation in magnetic materials. GIS with surge arresters to mitigate VFTOs implemented in [13]. A new arrangement for the disconnector switch contact system is presented in [14]. An electromagnetic resonator by flashing element fitted to the source of VFTOs is presented in [15]. In [16], a mathematical model was developed to examine the effect of the amplitude-frequency of Vacuum Fault Interrupters on power transformers in both 500 kV and 800 kV Gas Insulated Switchgear was analysed using FORTRAN and Electromagnetic Transients Program. The ability of the shunt resistor in the 800 kV GIS to reduce Vacuum Fault Interrupters was verified. By comparing the results from both EHV systems, this research provides valuable insights for advancing the localization of UHV utilities and GIS manufacturing and helps to facilitate the implementation of UHV transmission networks.

In [17], the modeling of GIS substations and the topic of overvoltage generation during switching with and without load was discussed, and a cost-effective approach to suppressing very fast transients in power transformers connected to gas insulated substations was presented in a 2016 study at Curtin University in Perth, Australia. Japan is planning to implement the use of a resistor in a disconnector of gas-insulated switchgear (GIS) as part of its efforts to install 1000 kV transmission lines, which will help in suppressing very fast transient (VFT) phenomena. The efficacy of the resistor in controlling VFT overvoltage has been determined and the necessary function of the resistor has been established. To validate this, a charging current interruption test circuit was constructed, and a 1100 kV disconnector equipped with a resistor was subjected to testing [19].

This study proposes four methods to reduce Vacuum Fault Interrupters in 1200 KV rated Gas Insulated Substations and assesses them in terms of their rise time, peak value, and mitigation time. The techniques were explored at disconnector switches in 1200 KV GIS. The performance of each component in the substation was evaluated with regards to high frequency transients by utilizing an equivalent circuit model. The design and modelling of substation elements are detailed in section 2, the four mitigation techniques are described in section 3, and simulation results using MATLAB/SIMULINK are presented and evaluated in section 4.

2. Generation Process and Types of VFTO

The switching of busbars and the operation of circuit breakers are critical tasks that take place frequently within a substation and are performed using disconnector switches. The likelihood of these switching is very high. Typically, the switching of disconnector switches or circuit breakers does not result in overvoltage transients in conventional air-insulated switchgear (AIS) substations. However, in gas-insulated switchgear (GIS) substations, the switching of disconnector switches that lack arc suppression capability can potentially cause very dissolute passing overvoltage's, In China, the use of 500 kV Gas Insulated Switchgear (GIS) has been plagued by numerous internal breakdowns and equipment failures due to frequent Voltage Fed Transfer Oscillations (VFTOs), which are commonly referred to as VFTOs. As examples, in 1992, The rapid transient over-voltage during system switching at the Guangdong Daya Bay Nuclear Power Project resulted in damage to the main insulation of the main transformer. Another incident occurred in 2001 at the Zhejiang Beilun Power Plant, where a 500 kV transformer was damaged because of an extremely fast transient over-voltage.

Circuit breakers in GIS or HGIS substations have good arc suppression performance, enabling discharge restriking, so the overvoltage created in the process can be disregarded. However, the potential for VFTOs generated during the operation of disconnector switches should be taken into consideration.

The peak magnitude of the VFTOs is given as

$$u_{max} = K.u_s - u_{TC} \leq 3.0p.u$$

In the equation:

K represents the oscillation or overshoot factor, with a range of 0 to 2.

u_{TC} represents the voltage of residual charge, with a range of -1.0 pu. to 1.0 pu.

u_s represents the line voltage.

intended for 1200 kV UHV GIS: $\mathbf{1\ p.u = 1200 \times 1.1/\sqrt{3} \times \sqrt{2} = 980\ kV}$.

In extreme conditions, while the disconnector switch is closing, $u_{TC} \Longrightarrow 1pu$, $u_s \Longrightarrow 1pu$, $K \Rightarrow 2$ then, $\Delta u \Rightarrow 2pu$ and $u_{max} \Longrightarrow 3.0\ p.u.$

The frequency of VFTOs oscillation depends on the parameters of the substation and the layout of the GIS. During the opening and closing operation, The abrupt increase in the voltage wave travels equally to The disconnector switch has open connections on both sides of its busbars and its transmission speed is slightly slower than the speed of light.

The characteristics of VFTO, based on the generation mechanism of VFTO and the properties of GIS equipment, are as follows:

1. Rapid striking and restriking process of arc.
2. The peak level of VFTO can reach as high as 3.0 p.u.
3. The VFTO consists of high-frequency transients which fall within the frequency range of 30 kHz to 100 MHz.
4. The appearance of VFTO is associated with the restriking and arc extinguishing moments of the disconnector in the GIS system, as well as the placement of the disconnector nodes within the GIS equipment.

5. Modelling of 1200 KV Substation

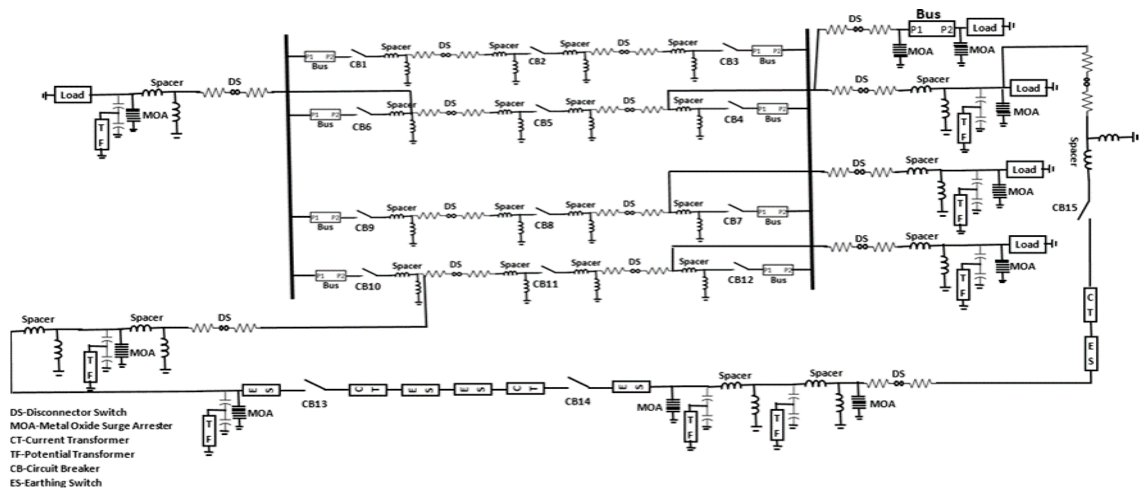


Fig 1. Diagram of a particular way for a 1200KV substation.

The effects of VFTOs at the 1200 KV test station in Bina, Madhya Pradesh. India, has been addressed by incorporating additional protection devices such as MOVs. Figure 1 shows a diagram of a single line for the 1200 KV test system. The testing facility comprises two sets of 1200 KV transformers and a single-circuit 1200 KV transformer. The surge impedance loading at the 1200 KV station is 2.5 times greater than that of a 765 KV substation and 11.5 times higher compared to a 400 KV substation.

3. Suppression techniques

3.1. Suppression of VFTOs Using Resistance

An additional resistor can be added in series with the disconnector switches during switching operations at GIS substations to suppress VFTOs. This increases the resistance in the path of the propagating waves, which reduces the rate of change in their magnitude and frequency of occurrence. The value of the resistor can be chosen based on the frequency and magnitude of the propagating waves.

Spark resistance between contacts of disconnector switch during switching operation is given as

$$R_{spark} = R_0 e^{-\frac{t}{c}} + R_f \qquad (4)$$

$\boldsymbol{R_o}$ *is equal to* 108Ω, *and* R_f *is a constant resistance ranging from* $0.5\ \Omega$.

Decreasing leakage current through arc or spark between contacts can be achieved by increasing spark resistance. By adding external resistance in series with a disconnector switch, the resistance path for leakage current is increased, which reduces the maximum value of transient over voltages.

3.2. Using RC Filter

An RC filter connected to a load on the consumer side creates a low-resistance path for high-frequency oscillations to ground. Similarly, an RC filter connected in parallel with a disconnector switch also creates a low-resistance path for high-frequency oscillations, which helps to ground transients. This redirects high-frequency transients into the ground, reducing VFTOs. The resistance used in this method is not frequency-dependent, and when the appropriate value is selected, it functions as a dampener of high-frequency oscillations.

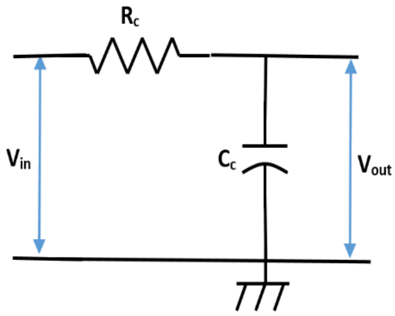


Figure 2. RC filter

The voltage amplification of the RC filter is expressed as.

$$\frac{v_{out}(s)}{v_{in}(s)} = \frac{\frac{1}{R_c C_c}}{s + \frac{1}{R_c C_c}} \quad (5)$$

the frequency response of the RC filter can be expressed as.

$$f_c = \frac{1}{2\pi R_c C_c} \quad (6)$$

The time constant is expressed as.

$$r = R_c C_c = \frac{1}{2\pi f c} \quad (7)$$

3.3. Ferrite Rings

Ferrite rings can be applied over the contacts of disconnector switches to reduce the magnitude and gradient of VFTOs. This is a flexible, fast, viable, and efficient process. Ferrite rings reduce the spread of traveling waves along a conductor by resisting high-frequency voltage spikes. The resistance provided by the ferromagnetic material changes with frequency due to the permeability and inductance of the rings. By adding inductance and resistance to the disconnect switch, the effectiveness of ferrite rings in decreasing VFTOs is enhanced.

Impedance by ferrite rings on VFTOs is given as

$$Z_f = R_f + 2\pi f L_f = j2\pi f L_e \quad (8)$$

L_e is equivalent inductance, f frequency of transients

$$Z_f = j2\pi f \mu_r L = j2\pi f L(\mu_s' - j\mu_s'') = 2\pi f L \mu_s'' + 2\pi f L \mu_s' \quad (9)$$

Where L is inductance of the ferrite ring

$$L = \frac{\mu_o d}{2\pi} L \frac{R}{r} \quad (10)$$

Ferrite rings serve as a low resistance route for fundamental signals at the base frequency, but a high resistance route for high-frequency voltage fluctuations. The behavior of ferrite rings is determined by factors such as frequency response, loss and saturation characteristics, and magnetic conductivity of the material. The equivalent circuit of a ferrite ring is shown in Figure 3.

To effectively suppress VFTOs, an appropriate equivalent inductance (Lf) should be calculated that offers high impedance to the traveling wave transmission. This inductance is determined by the magnetic conductivity, geometry of the ferrite rings, and busbar. Materials with high magnetic conductivity are crucial for obtaining high inductance values, but if the ferrite ring's performance in high frequency is inadequate, the high-frequency response will be insufficient, its equivalent resistance will be low, resulting in no decrease of VFTOs. If the equivalent resistance is high or infinite, the ferrite ring will only influence the slope of VFTOs, decreasing it, but not their amplitude.

The right balance of inductance and resistance can lead to high energy consumption of traveling waves and significant damping of voltage transients. The selection of ferrite material is crucial, as the magnetic saturation of the material can significantly affect the ability of ferrite rings to mitigate VFTOs. As wave current can reach thousands of amperes, it's important to choose the ferrite ring material cautiously to avoid excessive saturation when exposed to the passing waves. The material of the ferrite ring should be chosen carefully to prevent saturation from becoming excessive when it is subjected to the passing waves.

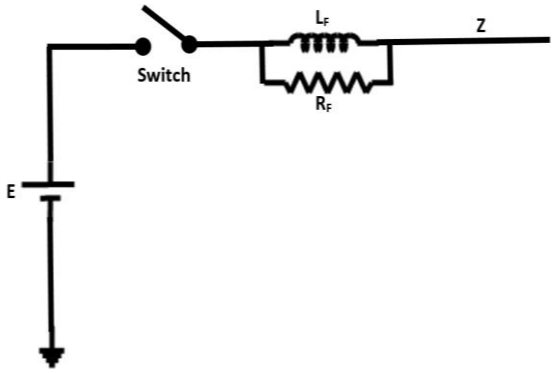


Figure 3. Equivalent circuit of Ferrite Rings

3.4. Nanocrystalline based Mitigation of VFTO

Nanocrystalline material is a polycrystalline with a crystallite size of only a few nanometers, it has improved rigidity, good electrical resistivity, less density, better flexibility, higher thermal expansion, and lower thermal conductivity. The Nanocrystalline material that is used to suppress VFTOs is made of silicon, iron and boron materials, and saturated in a magnetic field. When the current flows in conductors, the magnetic field strength of GIS is higher than the saturation field strength of nanocrystalline material and there is no energy loss in the nanocrystalline during the low frequency range. However, during the propagation of high-frequency VFTOs, energy loss due to the transients occurs and is mitigated. The rising anisotropy implementation of nanocrystalline rings creates micro eddy currents which cause losses, suppressing the transients. Figure 4 illustrates the equivalent circuit of the nanocrystalline rings. By simulating the GIS substations installed with ferrite rings, The resistance (Rd), inductance (Ld), and capacitance (Cd) values can be optimized to find the values that most effectively reduce voltage transients.

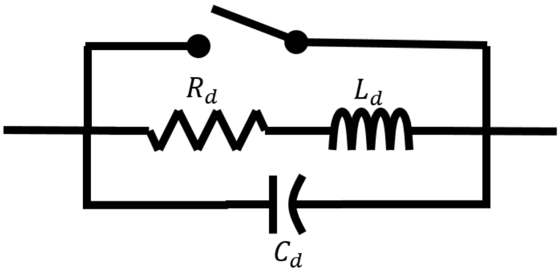


Figure 4. Circuit Equivalent of Nanocrystalline Ring.

Simulation Results

Simulations are performed on 1200KV substation to check the efficacy of proposed mitigation techniques for VFTOs. Substation is modelled using the behavior of components to high frequency transients. The simulation of VFTO's is performed by MATLAB/SIMULINK.

3.5. Mitigation of VFTOs in 1200 KV GIS by Resistance

Figures 5 and 6 display the VFTOs at various points in a 1200 KV substation, resulting Compare the effects of switching the CB1 disconnect switch with and without resistance as a mitigation system. Figure 5 Illustrates the voltage transients at the disconnector switches (CB1-CB15) and potential transformers (PT1-PT11) in the absence of any resistance, while Figure 6 shows the same transients with the implementation of resistance. The 530-ohm resistor value was chosen after testing the simulation of the system was performed using various resistor values. The table shows the magnitudes, settling times, and rise times of VFTOs for CB1-CB3 and PT1-PT3 with and without resistance. To validate the effectiveness of the proposed resistor value, Figure 7 presents the VFTOs for four different resistors at the B1 and B2 locations.

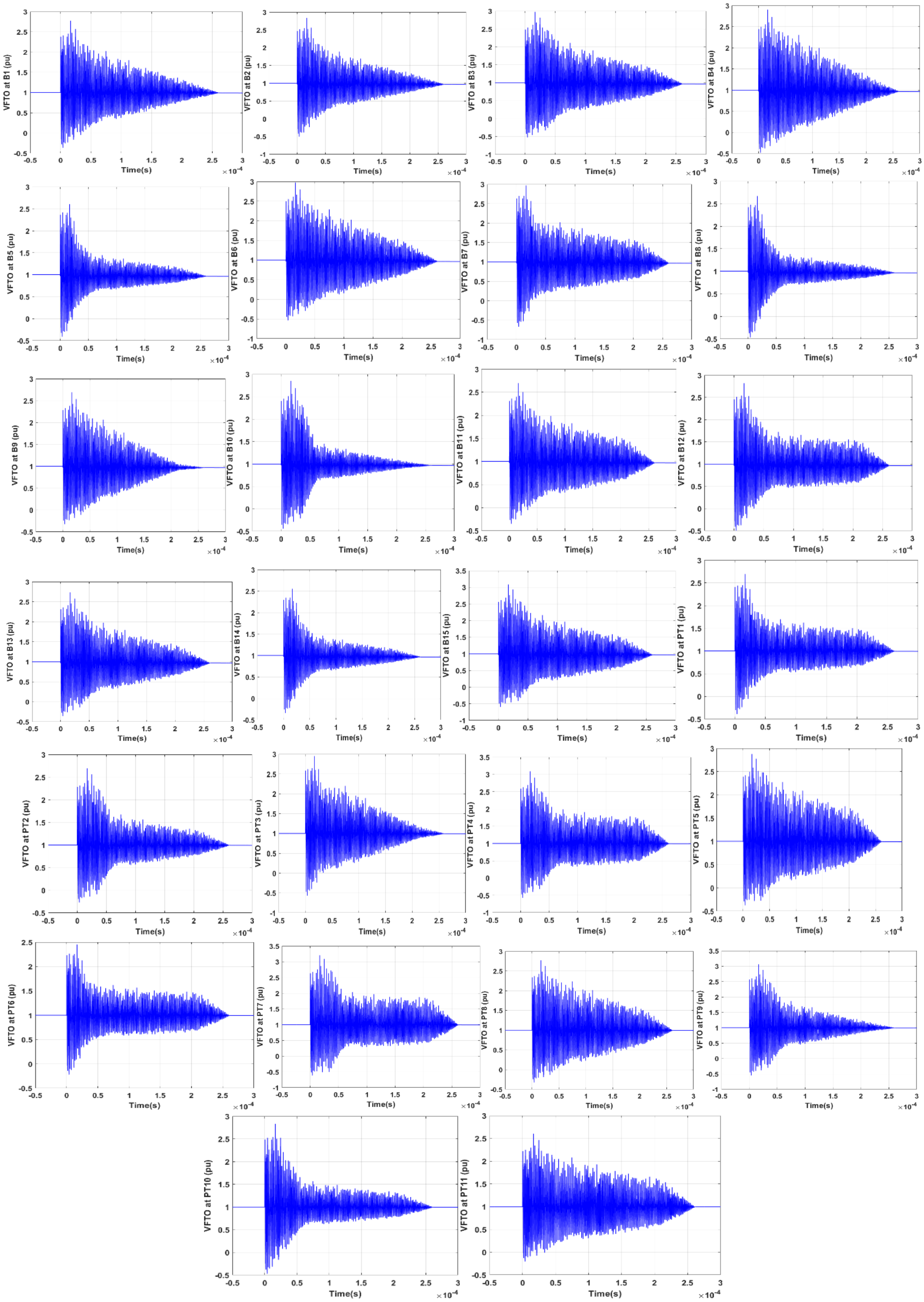


Fig 5. The voltage fluctuations at the disconnector switches (CB1-CB15) and potential transformers (PT1-PT11) are displayed in the absence of any mitigating device.

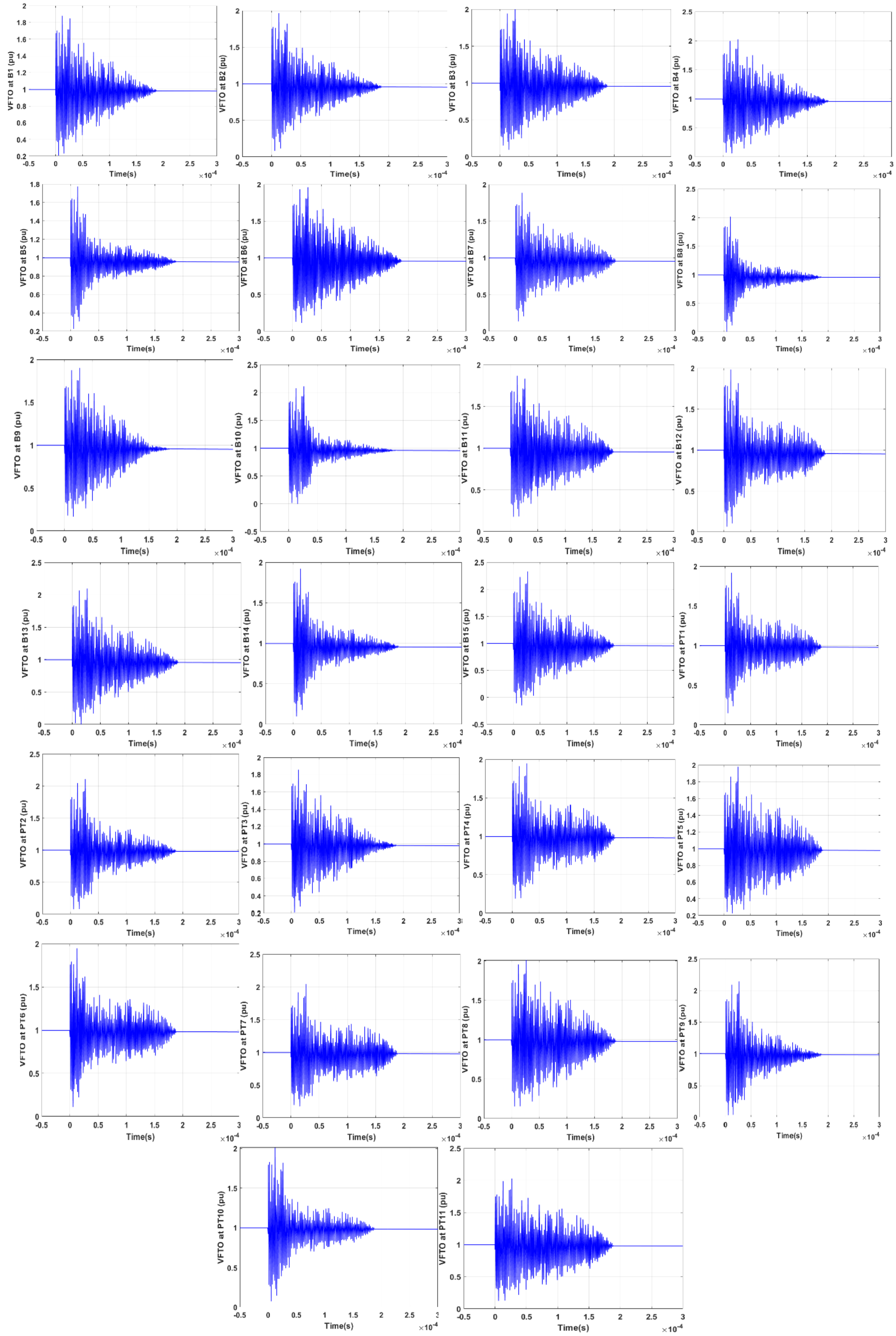


Fig 6. The voltage fluctuations at the disconnector switches (CB1-CB15) and potential transformers (PT1-PT11) are shown with the resistor serving as the mitigating device.

TABLE 1. Performance of Resistance as suppression device

Assessed location	Without additional resistance			With additional resistance as suppression device		
	Magnitude (p.u.)	Rise time (μ sec)	Settling time (μ sec)	Magnitude (p.u.)	Rise time (μ sec)	Settling time (μ sec)
CB1	2.8	1.79	250.6	1.90	1.20	184.9
CB2	2.3	1.63	246.8	1.3	1.20	199.25
CB3	2.9	1.79	252.2	2.05	1.26	187.36
PT1	2.5	1.68	244.62	1.80	1.25	180.20
PT2	2.85	1.77	251.12	2.07	1.28	184.64
PT3	3	1.70	246.23	1.8	1.4	185.67

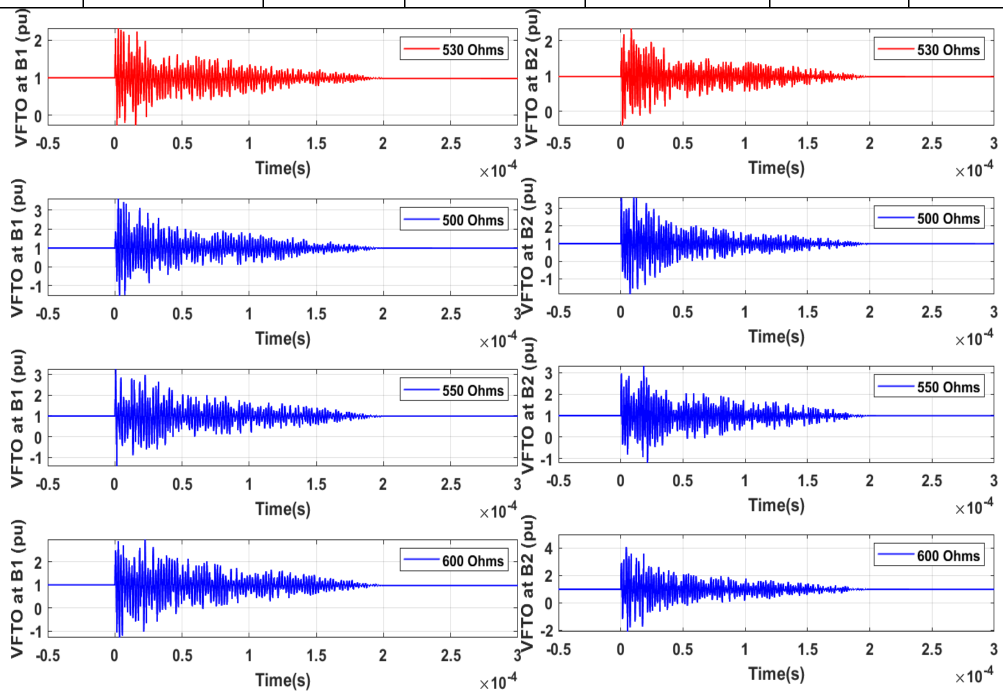


Fig 7. The voltage fluctuations at the B1 and B2 locations in the substation are displayed for four different resistor values.

Suppression of VFTOs in 1200 KV GIS by RC Filter

Figures 8 show the voltage fluctuations at the disconnector switches (CB1-CB15) and potential transformers (PT1-PT11) were mitigated by using RC filters. The optimized resistance value of 336 ohms and capacitance value of 1.148F were determined through analysis of the modelled system with different RC filter combinations. The magnitude of the VFTOs and A table presents the settling and rise times for CB1-CB3 and PT1-PT3 with resistance and with the use of an RC filter. Figure 9 shows the VFTOs at the B1 and B2 locations with four different RC filters, to verify the efficiency of the optimized resistance and capacitance values. The use of an RC filter as a means of mitigating voltage transients in the disconnector switch resulted in a 10% decrease in the magnitude of the transients and a 30-40 second reduction in settling time. The VFTO peak values, which ranged from 1.8-2.01 p.u. with just resistance, were reduced to 1.6-1.78 p.u. with the addition of the RC filter.

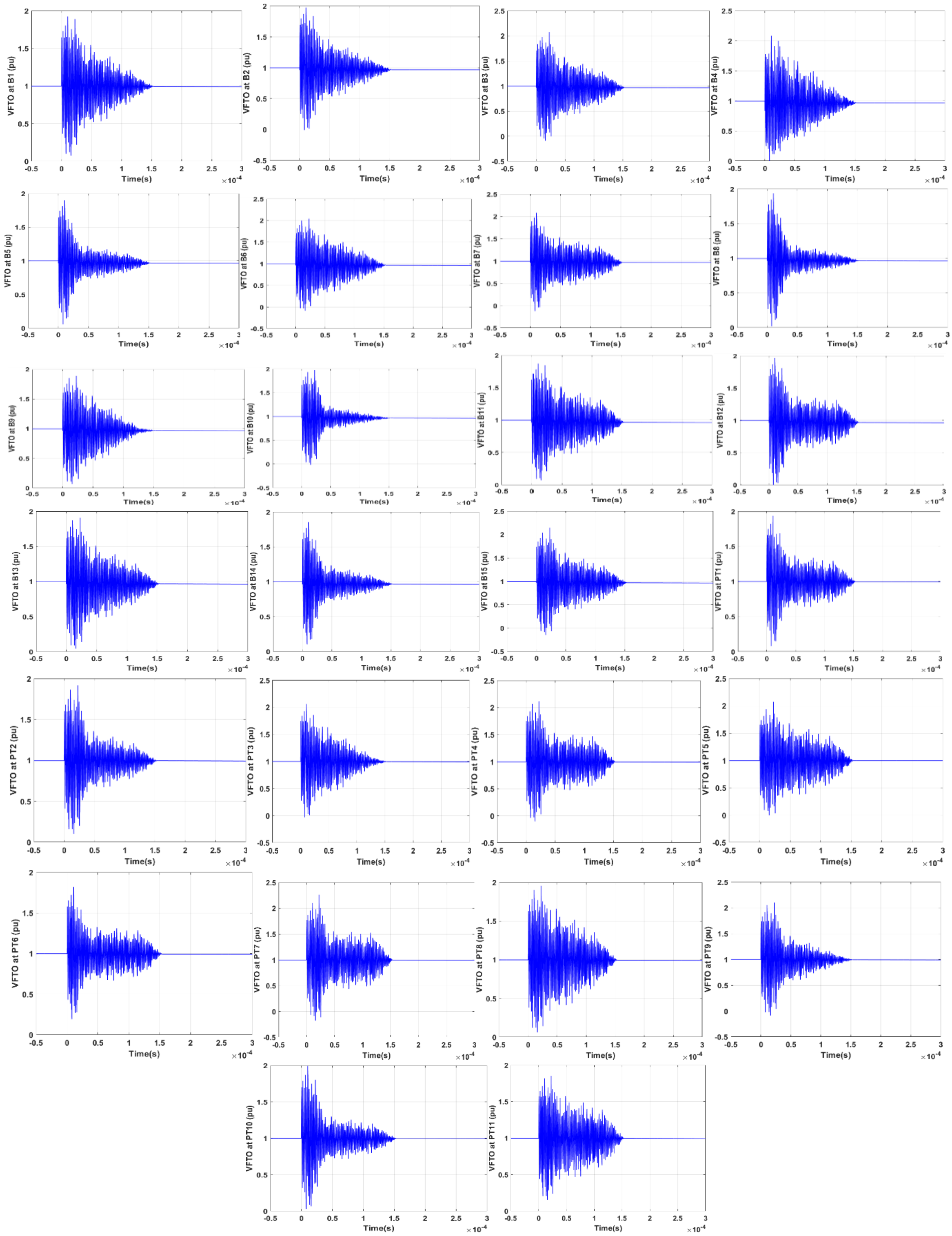


Fig 8. VFTOs at (CB1-CB15) and at (PT1-PT11) through RC Filter as suppressive method

Table 2. Performance of RC Filter like suppressive methods

Measured location	With the use of resistance as a suppressive method.			Through the utilization of an RC filter as a mitigation device in addition to resistance.		
	Magnitude (p.u.)	Rise time (μ sec)	Settlingtime (μsec)	Magnitude (p.u.)	Rise time (μ sec)	Settlingtime (μ sec)

CB1	1.98	1.29	185.4	1.80	1.20	150.6
CB2	1.6	1.15	196.26	1.73	1.15	154.33
CB3	2.08	1.30	186.40	1.83	1.185	155.1
PT1	1.88	1.26	180.22	1.8	1.191	150.86
PT2	2.06	1.22	185.66	1.4	1.17	146.6
PT3	1.7	1.4	184.67	1.74	1.180	155.06

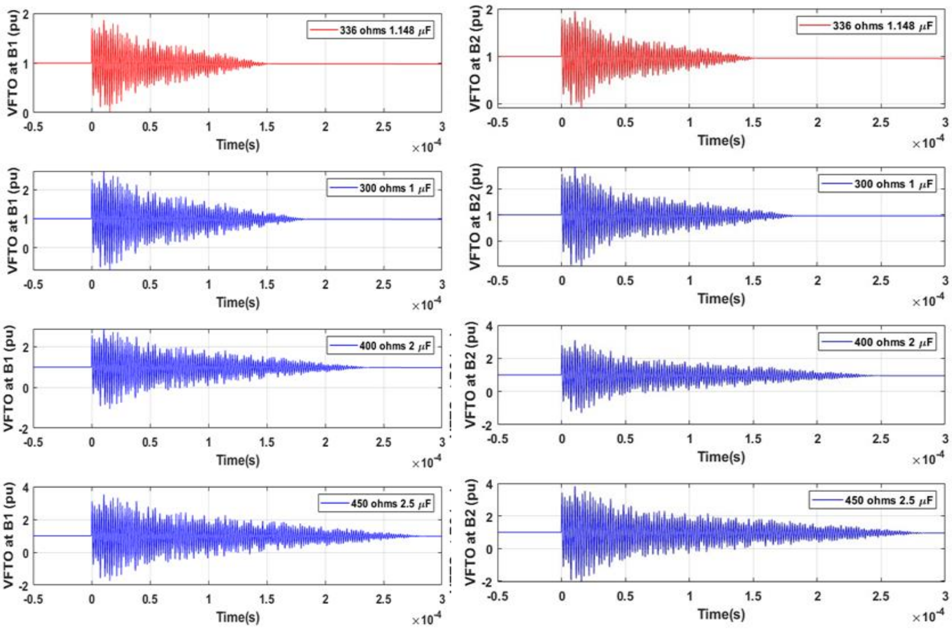


Fig 9. VFTOs at the B1 and B2 locations of the substation were measured for four different cases varying RC Filter standards are depicted.

3.6. Suppression of VFTOs in 1200 KV GIS by Ferrite Rings

The voltage transients at the CB1 disconnector switch of the 1200 KV substation after adding RC filter and ferrite rings are displayed in Figure 10.

The voltage transients produced during the switching at the results of the voltage transient reduction achieved through the implementation of Ferrite Rings at the disconnector switches (CB1-CB15) and potential transformers (PT1-PT11) are depicted in Figure 10. The best resistance and inductance values of 276 ohms and 2.33 millihenries, respectively, were established through analysis of the model system with different Ferrite Ring configurations. The performance of voltage transients at the disconnector switches (CB1-CB15) and potential transformers (PT1-PT11) in terms of their magnitudes, settling times, and rise times has been recorded, considering both resistance and the RC filter mitigation device.

The effect of combining RC filters and Ferrite Rings on the voltage transients at the CB1 disconnector switch in a 1200 KV substation is demonstrated in Figure 11. The figure illustrates the voltage transients at the disconnector switches (CB1-CB15) and potential transformers (PT1-PT11) when Ferrite Rings are employed.

The results of the analysis, which aimed to determine the optimal values for the 276-ohm resistor and 2.33 millihenry inductance, are presented in a table. The data shows the magnitude of voltage transients and the settling and rise times for CB1-CB3 and PT1-PT3 with resistance and the RC filter, taking into account the various Ferrite Ring values used in the model. The adding of Ferrite Rings along with improved values resulted in a 13% reduction in voltage transient magnitudes and 20-30 second reduction in settling times, compared to using only RC filters. The magnitude of the voltage transients at the peak level, which was previously between 1.6 to 1.8 p.u. with the use of RC filters, was reduced to a range of 1.4-1.6 p.u. with the implementation of Ferrite Rings.

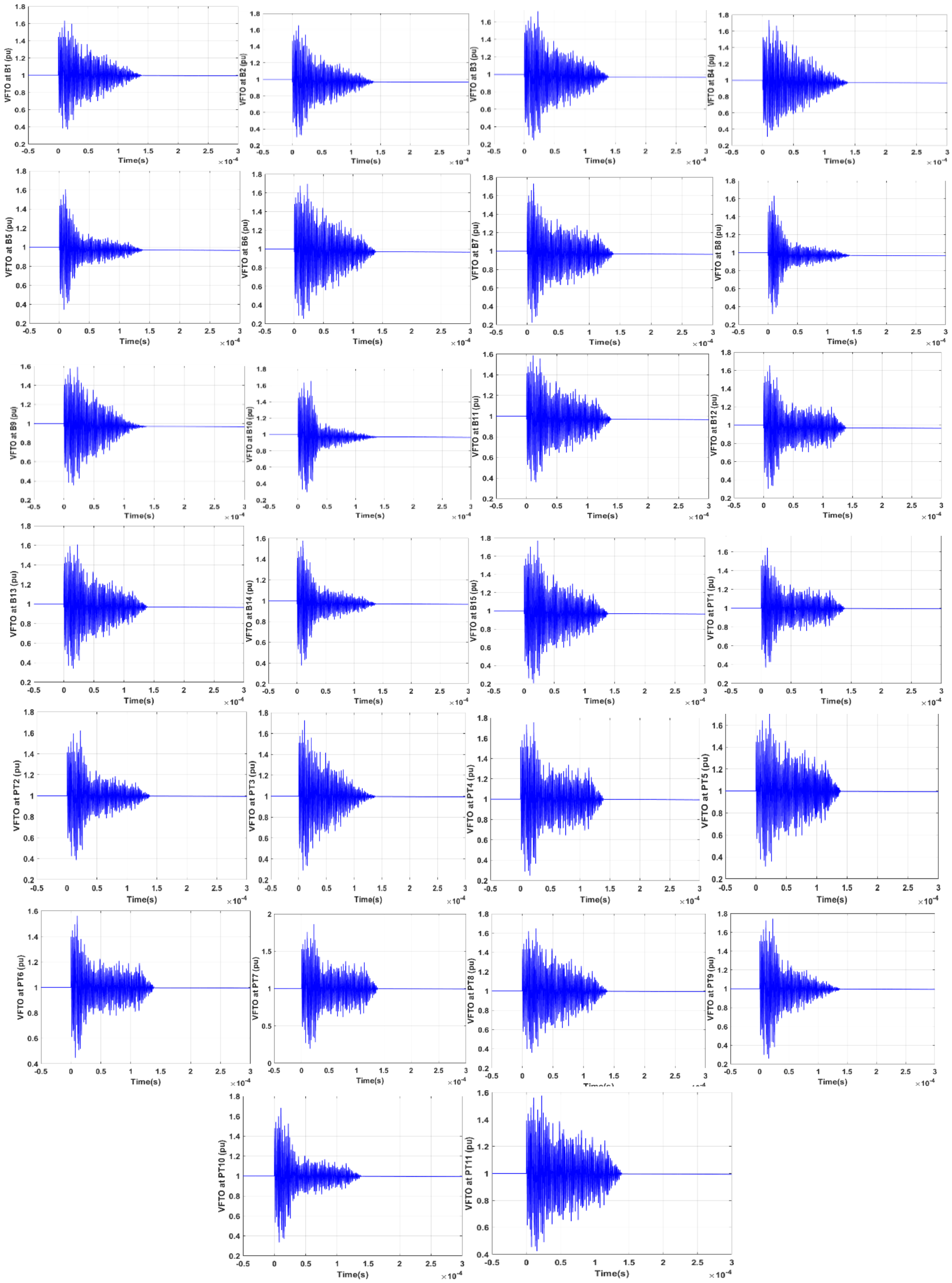


Fig 10. The figures display the voltage transients at the disconnector switches (CB1-CB15) and potential transformers (PT1-PT11) with the implementation of Ferrite Rings as a mitigating device.

Table 3. Performance of Ferrite Rings as suppression device

Measured location	With the utilization of an RC filter as a mitigation device in addition to resistance.			With the addition of Ferrite Rings as the suppressive method.		
	Magnitude (p.u.)	Rise time (µsec)	Settlingtime (µsec)	Magnitude (p.u.)	Rise time (µsec)	Settling time (µ sec)
CB1	1.80	1.20	151.6	1.60	1.19	139.5
CB2	1.65	1.18	155.32	1.48	1.05	134.5
CB3	1.74	1.177	155.1	1.64	1.13	135.63
PT1	1.5	1.188	150.83	1.50	1.109	138.4
PT2	1.2	1.14	146.8	1.3	1.17	132.89
PT3	1.69	1.180	154.02	1.48	1.111	130.59

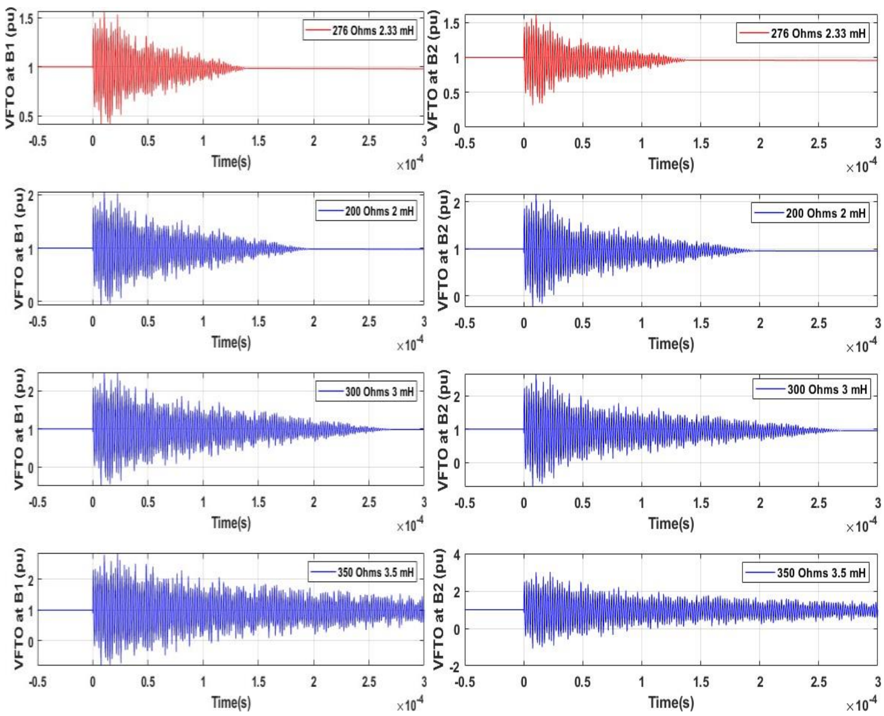
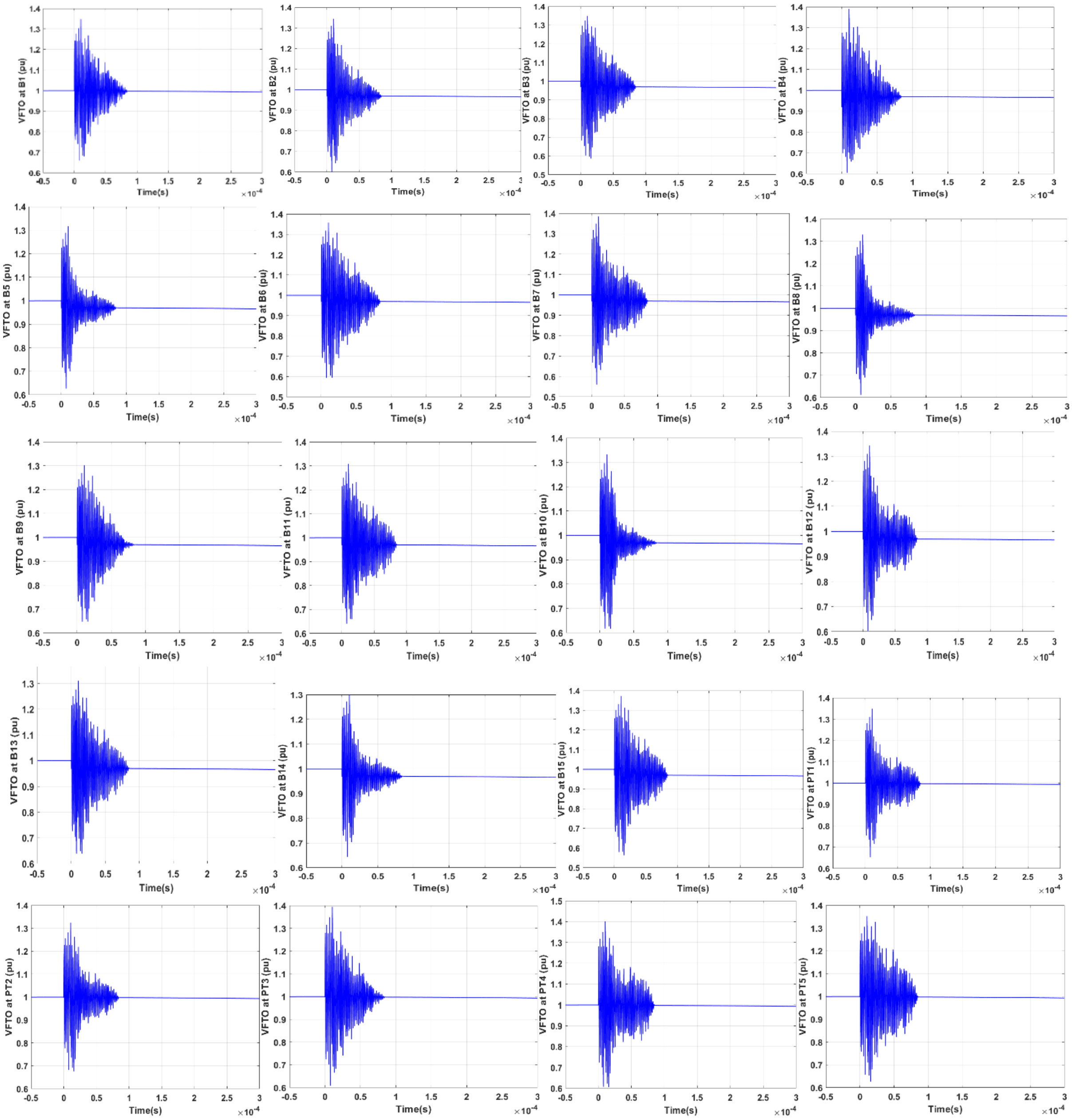


Fig 11. Figures display the VFTOs at B1 and B2 of the substation for four different combinations of resistor and inductor values utilized in the Ferrite Rings.

4.8Mitigation of VFTOs in 1200 KV GIS by NanocrystallineRings

Figures 12 The figure depicts the voltage transients that occur at the disconnector switches (CB1-CB15) and potential transformers (PT1-PT11) when nanocrystalline modules are utilized.

The ferrite rings have a resistance of 276 ohms and an inductance of 2.33mH, while the nanocrystalline rings exhibit a resistance of 183 ohms, an inductance of 3.26mH, and a capacitance of 2.855F. The document records the magnitudes of the voltage transients and the settling and rising times of CB1-CB3 and PT1-PT3 with the use of both ferrite rings and nanocrystalline rings as mitigation devices. Figure 13 displays the voltage frequency tunable oscillators (VFTOs) The impact of using nanocrystalline rings as mitigating devices in disconnector switches is evaluated by examining the voltage transients at B1 and B2 positions for four different nanocrystalline ring configurations, considering the suggested resistance, capacitance, and inductance values. The replacement of ferrite rings with nanocrystalline modules results in a significant reduction of 20% in the magnitude of voltage transients and a substantial decrease of 40-50 seconds in the settling time.



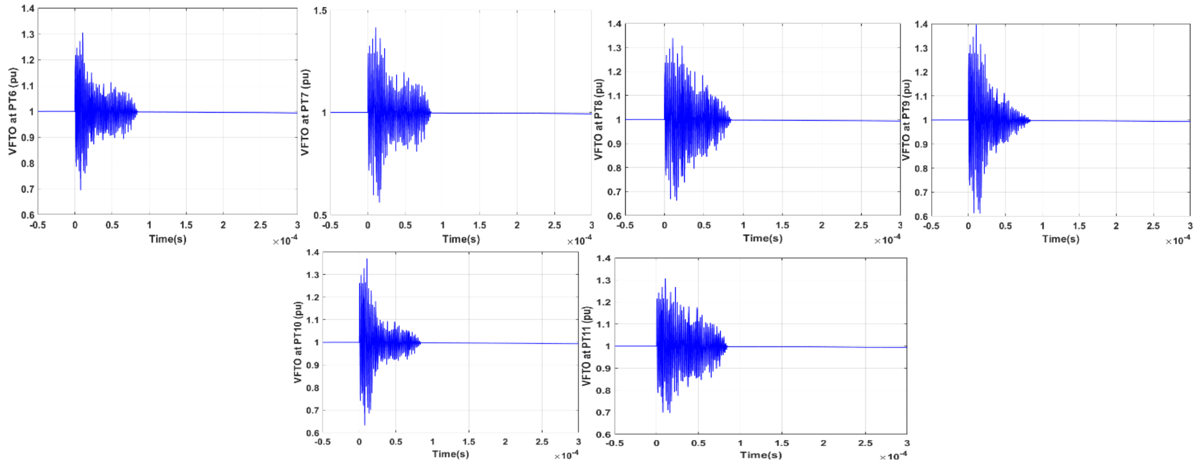


Fig 12. **A 1200 KV substation employs nanocrystalline modules to mitigate voltage transients at its disconnector switches (CB1-CB15) and potential transformers (PT1-PT11).**

Table 4. Performance of Nanocrystalline rings as suppression device

Measured location	In addition to Ferrite Rings as suppressive method			With added Nanocrystallineas a suppressive method		
	Magnitude (p.u.)	Rise time (µ sec)	Settlingtime (µ sec)	Magnitude (p.u.)	Rise time (µ sec)	Settling time(µ sec)
CB1	1.53	1.19	134.4	1.4	0.897	77.31
CB2	1.49	1.04	137.6	1.35	0.752	64.6
CB3	1.66	1.10	130.67	1.7	0.799	62.72
PT1	1.50	1.107	135.6	1.33	0.814	75.16
PT2	1.2	1.13	133.88	1.37	0.812	77.07
PT3	1.48	1.119	130.59	1.4	0.796	70.14

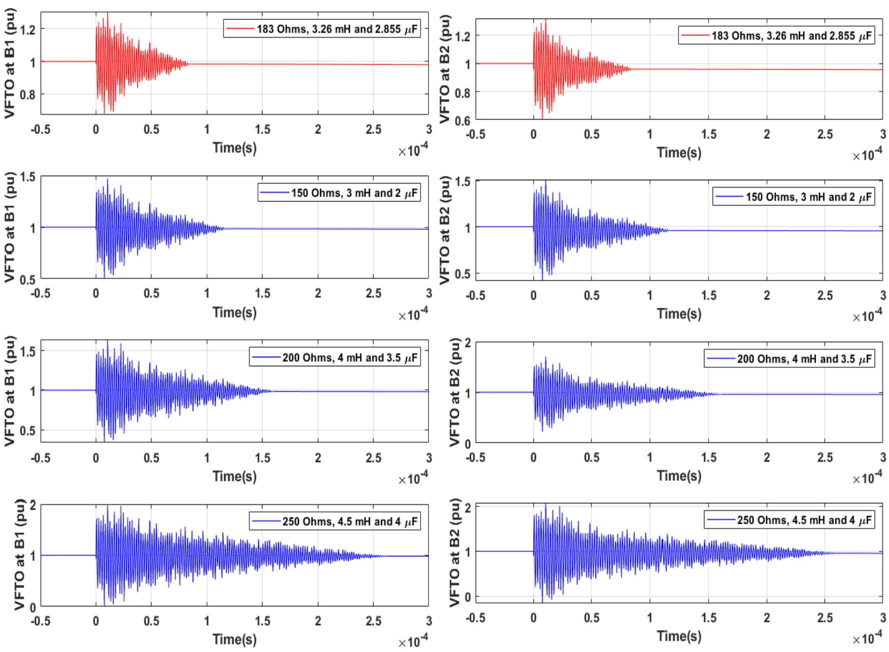


Fig 13. Figure 13 depicts the voltage frequency tuneable oscillators (VFTOs) combinations of resistance, inductance, and capacitance in the nanocrystalline device on voltage transients at the B1 and B2 positions in the substation.

4.Conclusion

In extra high voltage GIS substations where the relationship between impulse endure voltage and fundamental rated voltage is minimal, the impact of voltage transients (VFTOs) on equipment must be reduced. To mitigate the effects of VFTOs in a 1200KV EHV substation, four suppression techniques are proposed, and their efficacy is evaluated based on the peak magnitude, rise time, and settling time of the oscillations. By performing simulations on a 1200KV substation, the optimal parameter values of these methods can be determined. Different sections of the substation are evaluated based on their performance for high-frequency oscillations. From the simulation results and comparison, it can be determined that the implementation of nanocrystalline rings as mitigating devices is more effective compared to the other three methods.

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