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Factors affecting the VFTOS and Suppressing Techniques using Lumped Elements in UHV GIS Substations

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Abstract:
the suppression of very fast transient overvoltage (VFTOs) in a 1500 KV ultra-high voltage gas insulated substation (UHV GIS) using four different devices is presented in this paper VFTOs occur repeatedly during the operation of disconnector switches, due to the rapid propagation of travelling waves through the switchgear and the reduction of dielectric strength of substation components. This can cause flashovers to nearby grounded items because of transient ground potential rise or transient enclosure voltages. To address this, four techniques for suppressing VFTOs in a 1500KV UHV substation are presented, and the efficacy of these devices is assessed based on the peak value, rise time, and settling time of oscillations. The simulation is performed on a 1500KV substation using MATLAB/SIMULINK.

1. Introduction

A gas insulated substation (GIS) is a type of electrical substation in which the electrical equipment is enclosed in sealed compartments filled with a dielectric gas, typically sulfur hexafluoride (SF6). The use of a gas insulation system, rather than traditional air insulation, provides several advantages such as compactness, high reliability, and a reduced risk of environmental contamination [1].

In a Gas Insulated Substation (GIS), the high voltage equipment such as transformers, switchgears, and circuit breakers are housed within compartments that are hermetically sealed and filled with sulfur hexafluoride (SF6) gas. The SF6 gas provides excellent insulation properties and helps reduce the substation equipment’s size, making it possible to build compact substations that take up less space. The sealed compartments also help to protect the equipment from the environment, reducing the risk of damage from weather and other external factors [2].

GIS is mainly used in urban and densely populated areas, where the available space is limited. They are also used in offshore and underground substations due to their compactness, reliability, and safety. Gas Insulated Substation (GIS) technology has also been utilized in high-voltage direct current (HVDC) systems.

However, GIS has some limitations such as the high cost of installation and maintenance, and potential environmental concerns related to the use of SF6 gas, which is a potent greenhouse gas [4]. The primary environmental concern associated with GIS is the leakage of sulfur hexafluoride (SF6) gas, which has a potent greenhouse effect. With a global warming potential that is 23,500 times higher than carbon dioxide (CO2), it poses a significant threat to the environment. Therefore, there are regulations in place to limit the leakage of SF6 gas in GIS [5].

VFTOs, or very fast transient overvoltage’s, can have a significant impact on gas insulated substations (GIS). These transients are characterized by high amplitude and short duration and can be caused by a variety of factors such as lightning strikes, power grid switching, and equipment failures [6]. In a GIS, the high-voltage apparatus for instance transformers, switchgear, and circuit breakers are enclosed in sealed compartments filled with SF6 gas, which provides excellent insulation properties. However, VFTOs can still penetrate the gas insulation and cause damage to the equipment. The high voltage equipment in GIS is more susceptible to the VFTOs as they are operated at high voltage and high frequency [7].

VFTOs are a type of electrical transient that can cause significant damage to electrical equipment.

They are characterized by their high amplitude and short duration and can be caused by a variety of factors such as lightning strikes, power grid switching, and equipment failures [8].

Research on VFTOs has focused on several areas, including:

1. Characterization: Studies have been conducted to better understand the nature and behavior of VFTOs, including their amplitude, duration, and frequency characteristics.
2. Causes: Researchers have studied the various factors that can cause VFTOs, such as lightning strikes, power grid switching, and equipment failures, to identify possible sources of the transients.
3. Protection: Many studies have been conducted to develop and evaluate various protection devices, such as transient voltage surge suppressors (TVSS) and protective relays, to protect against VFTOs.
4. Impact: Research has been conducted to evaluate the impact of VFTOs on electrical equipment and systems, including the potential damage they can cause, and the costs associated with that damage.
5. Modeling: Researchers have developed mathematical models to simulate the behavior of VFTOs and their interactions with electrical equipment, which can be used to evaluate the performance of protection devices and to design and optimize new ones.

Overall, VFTOs are a complex phenomenon that requires a multidisciplinary approach to understand and protect against. The studies are done mainly on the protection devices, their efficiencies, and their performances [9]. There have been several studies on the impact of VFTOs on gas insulated substations (GIS) in the literature. These studies have focused on several key areas, including:

1. VFTO sources: Some studies have investigated the various sources of VFTOs in GIS, such as lightning strikes, power grid switching, and equipment failures.
2. VFTO measurement: Other studies have focused on measuring VFTOs in GIS environments and characterizing their amplitude, duration, and frequency characteristics.
3. Impact on GIS components: Some studies have evaluated the impact of VFTOs on various components of GIS, including the potential damage they can cause, and the costs associated with that damage.
4. Protection strategies: Many studies have investigated various protection strategies for GIS against VFTOs, including the use of surge arresters, transient voltage surge suppressors (TVSS), and protective relays.
5. VFTO modeling: Some studies have developed mathematical models to simulate the behavior of VFTOs and their interactions with GIS components, which can be used to evaluate the performance of protection devices and to design new ones.
6. Case studies: Some studies have reported case studies of VFTO incidents in GIS and the impact of these incidents on the GIS and the power system.

Overall, the literature suggests that VFTOs are a significant concern for GIS and that effective protection strategies are needed to mitigate the potential damage they can cause. The studies have shown that protection devices such as surge arresters, TVSS and protective relays can provide adequate protection against VFTOs. It is crucial to undertake routine maintenance and inspections of the components in a Gas Insulated Substation (GIS) to guarantee their proper functioning and ability to withstand very fast transient overvoltage (VFTOs).

A technique for curbing very-fast transient overvoltage (VFTO) in gas-insulated switchgear (GIS) is presented, involving the utilization of magnetic rings on the centre conductor is presented as a simpler and more reliable alternative to using a shunt resistor. The study, published in the IEEE Trans. Power Deliv in 2013 [10], used two types of Materials with magnetic properties that are capable of functioning at high frequencies: ferrite R2KB and amorphous FJ37.

The switching of disconnectors and occurrence of various faults within a Gas Insulated Substation (GIS) can result in multiple pre-strikes and re-strikes, causing short-lived voltage collapses and leading to the propagation of traveling surges in the busbar. This can lead to the emergence of Very Fast Transient Over voltages (VFTO) and Very Fast Transient Currents (VFTC) in Gas Insulated Substation (GIS) substations. Reducing the amplitudes of these VFTO and VFTC is a significant challenge. In the past, several methods have been proposed and tested such as using damping resistors and ferrite rings to address this issue, as per the study in [11].

According to a study [12], various approaches have been proposed and examined to curb very fast transient overvoltage (VFTO) in gas-insulated switchgear (GIS). The current state-of-the-art methods primarily aim to dissipate the energy of the electromagnetic waves that give rise to VFTO. However, the study introduces a new concept for VFTO mitigation that involves controlling the voltage conditions preceding the voltage breakdown in sulfur hexafluoride (SF6) gas, which triggers the generation of VFTO.

The occurrence of very fast transient over-voltages (VFTO) is a significant issue during the switching of unloaded sections with disconnectors in gas-insulated switchgear (GIS), as reported by in [13]. When disconnectors are switched in Gas Insulated Substation (GIS), there can be a varying number of pre-strikes and re-strikes, which cause short-lived voltage collapses and the propagation of traveling surges in the busbar duct. These Very Fast Transient Over-voltages (VFTOs) can act as the limiting dielectric stress that sets the dimensions in ultra-high voltage levels.

According to [14], large power plants are being constructed across the nation and the considerable amount of electricity that must travel several thousand kilometers from the source to the final consumers in major cities results in substantial power line losses. The State Grid Corporation of China (SGCC) has set a goal of utilizing 1100 kV as the voltage level for alternating current transmission to minimize these losses, thus taking a step into a new frontier of electrical grids.[15] introduced a technique for determining the breakdown voltage characteristics (BDV) of a disconnector in a gas-insulated switchgear (GIS). This approach can be utilized to model the very fast transient over voltages that occur during the opening and closing operations of the Disconnector.

[16] presented the initial full-scale experimental validation of the capability of high-frequency resonators to reduce very fast transient (VFT) waves in gas-insulated switchgear (GIS). The study utilized the numerical eigenvalue analysis method, which was implemented using COMSOL, to design and optimize the high-frequency (HF) resonators. The validity of the resonance frequencies calculated using this method was confirmed by comparing it to an alternative finite-difference time-domain method that was implemented using CST Microwave Studio. The mitigation of Very Fast Transient Overvoltage (VFTOs) in a 1500 KV ultra-high voltage gas-insulated substation (UHV GIS) is presented (UHV GIS) using four different devices is presented in this paper.

2. Modeling of GIS Components

2.1. Power Transformer

When modeling power transformers, the impulse voltage traveling wave can greatly impact the transformer's inner voltage distribution and electrostatic properties. To accurately model the transformer, non-linear characteristics resulting from the distribution of impulse voltage must be taken into account, as the windings of the transformer behave as a capacitive network at high frequencies and must be considered in conjunction. To properly model the transformer's response to impulse voltage traveling waves, the equivalent circuit should include factors such as When considering the power transformer, it is crucial to factor in the series and shunt capacitance, surge impedance, velocity of propagation, and formative time. By incorporating the properties of traveling waves and electrostatics, the capacitance and inductance of the transformer can be precisely defined.

$$L_t = \frac{\mu 0}{2\pi}\left[ln\frac{2l}{R} - 1\right] \quad (1)$$

$$C_t = \epsilon_o \epsilon_r \left(\frac{wl}{d}\right) \quad (2)$$

The limitations of a transformer be able to determine using the model of Very Fast Transient Overvoltage (VFTOs) for improved simulation performance. An illustration of the equivalent circuit for a power transformer in VFTO research is shown in Figure 1.

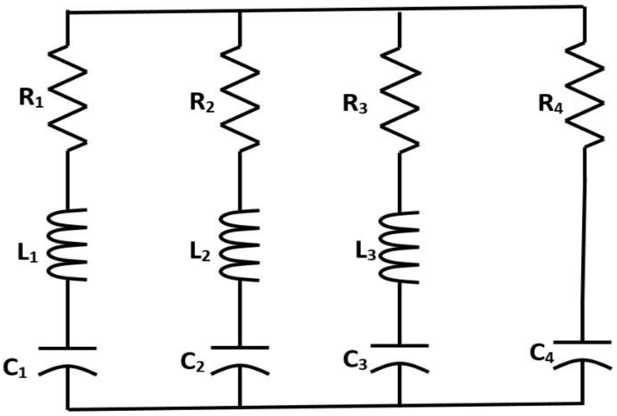


Figure 1. Equivalent Circuit representation of Power Transformer

2.2 Disconnector Switch

GIS-type disconnector switches for three-phase systems are appropriate for use with voltages up to 220 KV, while those for isolated phase systems are suitable for voltages higher than 220 KV. The equivalent circuit of the switch should consider both the open and closed states of the switch. The rapid movement of the contacts can cause pre-strikes and re-strikes when the switch is disconnected, as well as sparks between the contacts due to the electric field. The speed at which the disconnector operates can affect the flow of a charging current through the spark occurs when the switch is closed, causing the spark to be extinguished as the gap between the contacts narrows. Hence, the open state of the disconnector switch can be visualized as a capacitor, and the closed state as a transmission line with no loss.

A resistance that decreases exponentially be able to utilize to represent the spark that occurs among interactions.

$$R_{spark} = R_o e^{-t/r} \qquad (3)$$

R_{spark} is spark resistance,

R_0 is equal to $10^8 \Omega$,

t is formative time,

r is time constant in range of 0.5 nano seconds.

The equivalent circuit of a disconnector switch, when it is in the closed state, is represented by a series resistance. When the switch is in the open state, it can be modeled as a capacitor connected between two breaking contacts. This is shown in Figure 2.

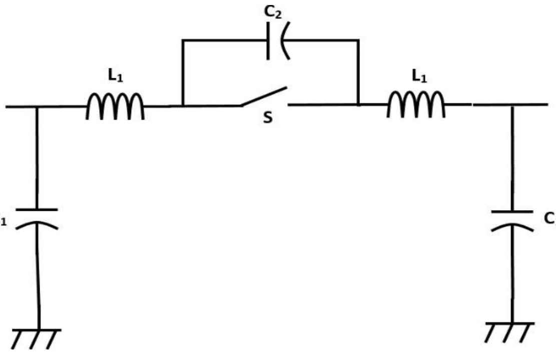


Fig 2. Equivalent Circuit of Disconnector Switch

2.3. Circuit Breaker

The functioning of a circuit breaker in the closed state can be represented as a transmission line without any losses, with a length equivalent to its physical size. When in an open state, it can be viewed as a series of capacitors with inherent flaws. For examining the switching transients, a circuit breaker is simulated by utilizing a pair of disconnector switches.

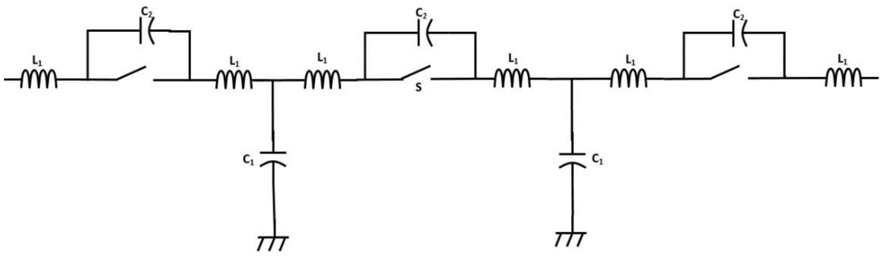


Figure 3 the equivalent circuit of Circuit Breakers, which is represented as a series of disconnector switches.

2.4. Metal Oxide Surge Arrester

Metal oxide surge arresters serve a dual role as both protection devices against lightning surges and as mitigation devices for very fast transient overvoltage. They can be designed as no-air-gap devices to dissipate the heat generated by arcing discharges. Arresters can be classified according to their effectiveness in mitigating surges and transient overvoltage. The current that flows through an arrester can be described as.

$$I = KV^{\alpha} \qquad (6)$$

K is ceramic constant,
α is nonlinearity exponent,
V is voltage across arrester,
I is current through arrester.

Equivalent circuit of surge arrester is shown in figure 4.

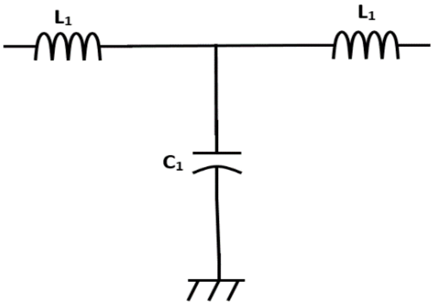


Fig 4. Equivalent Circuit of Surge Arrester

When modeling the behavior of Very Fast Transient Overvoltage (VFTOs), capacitance is the most critical parameter, as the busbar in a GIS system acts as a high-frequency transmission line that generates dominant oscillations in the tens of kilohertz to hundreds of megahertz range. Due to its shorter length compared to a traditional substation, it has a finite transit time and velocity of propagation at these high frequencies.

$$Z_s = In\left(\frac{b}{a}\right)\Omega$$

a is the diameter of HV bus and
b is the inner diameter of enclosure.

To accurately model the impedance during a surge caused by traveling overvoltage transients, it is important to take into consideration factors such as the wave propagation speed, the elemental duration, and the phase-to-ground capacitance in order to determine the dominant value. When creating a model of a UHV rated power transformer, the behavior of its high-frequency oscillations must be considered. Components such as spacers and elbows can be represented by a single capacitive value, while inductance, resistance, and capacitance can be used to represent the HV bushings. It is essential to account for factors such as wave propagation speed, elemental duration, and phase-to-ground capacitance to accurately determine the dominant value during a surge caused by traveling overvoltage transients.

When in the open state, circuit breakers can be modelled the closed state of a circuit breaker can be modeled as two transmission lines connected by an impedance, which replaces the capacitance, and a series resistance. To account for the behavior of a Gas Insulated Switchgear (GIS), an overhead line can be represented as a transmission line with a resistance equal to the surge impedance.

3. Modelling of 1500 KV Substation

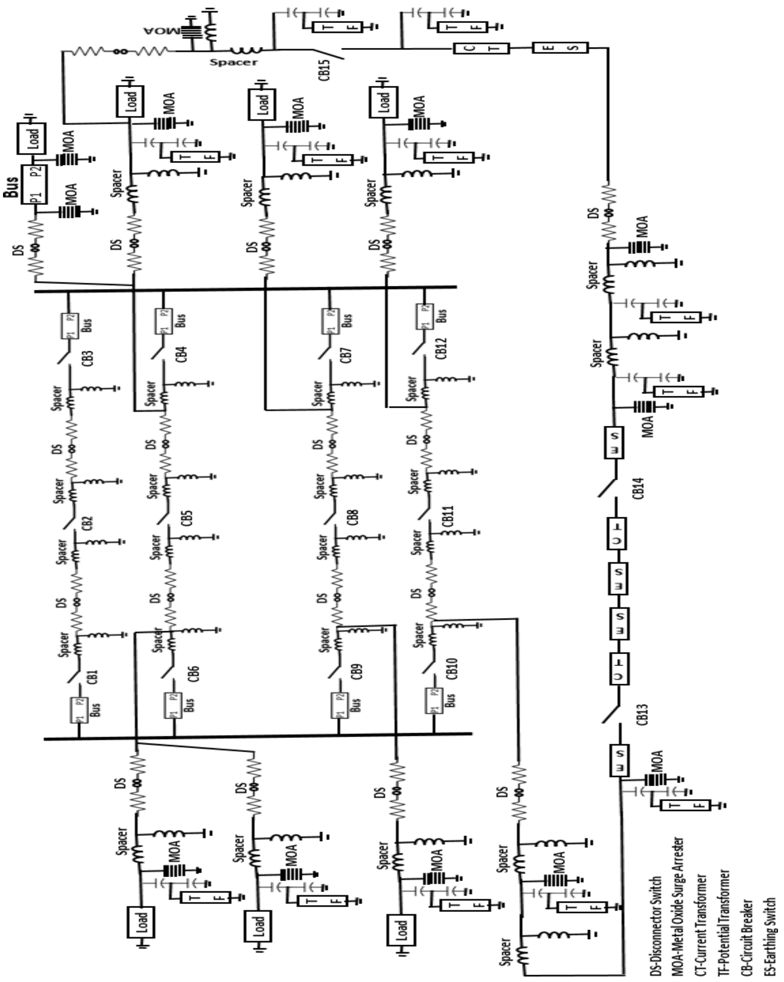


figure 5. diagram of a single line 1500 KV substation.

The 1500 KV test station in Bina, Madhya Pradesh, India has been evaluated for the impact of Very Fast Transient overvoltage's (VFTOs), and further protective measures, such as MOVs, have been implemented. The single line diagram of the 1500 KV substation with the additional safeguarding equipment is shown in Figure 5 [17]. The test station at Bina, Madhya Pradesh, India comprises of two sets of 1500 KV transformers and one single circuit 1500 KV transformer. The surge impedance loading of a 1500 KV substation is three times higher than that of a 765 KV substation and fourteen times higher than a 400 KV station. Meanwhile, the surge impedance loading of a 1200 KV station is 2.5 times greater than a 765 KV substation and 11.5 times higher than a 400 KV substation.

4. Suppression of VFTOs

4.1. Using Resistance

The key to reducing Voltage Transients on Overhead lines (VFTOs) is to add When the gap between the contacts is significant and the voltage discharge and transients are high, a resistor is placed in the discharge path to reduce the rate of change in the magnitude and frequency of refracted and reflected traveling waves when the disconnector switch is re-struck, which helps to lower VFTOs.

The resistance value required to suppress the VFTOs should be based on the peak magnitude and frequency of the VFTOs and the rise time. It is crucial to control the VFTOs when their peak exceeds the insulation level in ultra-high voltage Gas Insulated Switchgear (GIS) devices to ensure insulation coordination. A commonly used method for this is to install a damping resistor to reduce fast transients. The effectiveness of this technique in mitigating VFTOs is determined by the size of the damping resistor. When flipping on a disconnector switch, there may be an arc or spark between the contacts due to the resistance.

Increasing the resistance in the spark across the contacts will decrease the leakage current and thus decrease the introduction of a resistor in the discharge path can affect the frequency of the reflection and refraction of travelling waves, leading to a decrease in the peak value of VFTOs and a shorter rise time. This is why the use of a damping resistor with the appropriate resistance value is an effective technique to suppress VFTOs when flipping on a disconnector switch.

4.2. The reduction of VFTOs can be achieved using an RC filter.

RC filters are utilized frequently to protect loads from high-frequency transient surges. such as those induced by arcing in vacuum circuit breakers. They work by combining a resistance (R) and a capacitance (C) to attenuate high frequency components and filter out high frequency oscillations. When used in conjunction with a disconnector switch, the RC filter can redirect very high voltage transients and suppress them effectively.

The size of the resistance and capacitance in an RC filter is determined by the magnitude and frequency of voltage transients. An illustration of the typical RC filter interface structure is presented in Figure 6. The capacitance offers reactance that is inversely proportional to the frequency of high-frequency oscillations. An RC filter can effectively eliminate high-frequency oscillations by utilizing the inverse relationship between the reactance provided by the capacitance and the frequency of the oscillations. The capacitance acts as a circuit that allows these oscillations to be grounded, while the resistance acts to reduce the energy of these high-frequency oscillations by being frequency-agnostic and chosen with a suitable value. A typical RC filter interface structure is depicted in Figure 6.

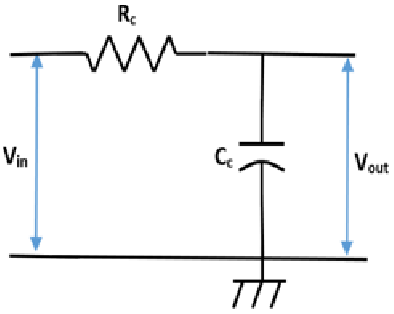


Fig 6. RC filter

Voltage gain of RC filter is given as

$$\frac{V_{out}(s)}{V_{in}(s)} - \frac{\frac{1}{R_C C_C}}{s+\frac{1}{R_C C_C}} \qquad (11)$$

And frequency response of RC filter can be defined as

$$\mathrm{I_C} = \frac{1}{2\pi \mathrm{R_C C_C}} \qquad (12)$$

And time constant is given as

$$r = R_C C_C = \frac{1}{2\pi f_c} \qquad (13)$$

The R and C parameters can be adjusted to optimize the RC filter for each of the four UHV substations. The goal is to effectively filter out high-frequency transients while still allowing low-frequency signals to pass through. The voltage gain and cut-off frequency can be used to determine the most effective values for the resistance and capacitance in the RC filter for each UHV substation. The basic structure and single line diagrams, as well as the constant parameters, will be adjusted accordingly, of these four substations have been obtained from literature sources [17].

4.3. Suppression of VFTOs by RC filter

Ferrite Rings

Ferrite rings are used to reduce electromagnetic interference (EMI) by providing impedance to high-frequency electromagnetic waves that travel through a conductor. They work by placing inductance and resistance in series with a conductor, which creates a low-pass filter that blocks high-frequency signals. When used in conjunction with a disconnector switch, ferrite rings can also provide protection against fast transients, such as voltage fluctuations caused by lightning strikes or power outages.

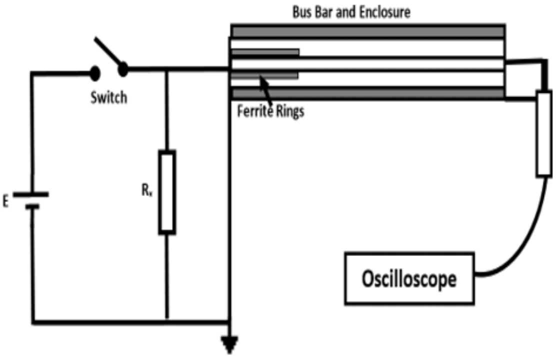


Fig 7. Dampening along with Ferrite Rings

Ferrite rings can effectively reduce the magnitude and rate of change of voltage fast transients (VFTOs) on the bus of a disconnecting switch by being connected around the bus. This method is practical, functional, cost-effective, and quick as it is easy to implement, and it does not require any additional complexity to the bus-bar design. Furthermore, using ferrite rings in GIS busbar, it helps in maintaining the integrity of insulation and protection of GIS components from overvoltage.

The selection of a ferrite ring for EMI suppression depends on the magnitude and characteristics of the VFTOs that need to be reduced. The impedance characteristics of ferromagnetic materials vary significantly with frequency. The impedance of ferromagnetic materials can be modeled using an equivalent series or parallel impedance, depending on the electromagnetic properties of the material. The series model is often preferred as it has a better frequency dependence compared to the parallel model. The impedance of a ferrite rings the resistance against the flow of electrical current provided by ferromagnetic materials, such as ferrite, against voltage fast transients (VFTOs) can be characterized as an impedance composed of resistance and inductance, which are influenced by their permeability coefficients. The permeability coefficient and the inductance of the ferrite material can vary depending on the frequency of the voltage. Ferrite rings are often used in VFTO protection to provide this impedance, and the specific impedance provided by a ferrite ring can be calculated using the material properties and dimensions of the ring.

$$Z_f = R_f + 2\pi f L_f = j2\pi f L_e \tag{14}$$

L_e is equivalent inductance, f is frequency of transients.

$$Z_f = j2\pi f \mu_r L = j2\pi f L\left(\mu'_S - j\mu''_S\right) = 2\pi f L\mu''_S + j2\pi f L\mu'_S \tag{15}$$

where L is inductance of the ferrite ring and can be expressed as

$$I = \frac{\mu_O d}{2\pi} I.\frac{R}{r} \tag{16}$$

To be effective in reducing the magnitude and rate of change of VFTOs, the ferrite rings used in protection must have specific characteristics to ensure satisfactory wideband performance and nonlinearity at high frequencies. The power frequencies of these ferrite rings typically fall in the hundreds of MHz range and do not affect the current base frequency. The frequency response, loss, saturation, and magnetic conductivity of the ferrite material all the specific characteristics of the ferrite rings are important in determining their ability to mitigate transient overvoltage.

The equivalent circuit of a parallel ferrite loop, as shown in Figure 8, illustrates the role of the equivalent inductance (L_f) in obstructing the circulation of the travelling wave. The value of L_f is affected by the magnetic conductivity of ferrite and the configuration of ferrite rings and busbar both play a role. This means that to achieve optimal VFTO protection, the design and selection of the ferrite rings must consider not only the material properties but also the geometry and configuration of the rings and the busbar. For the ferrite rings used in VFTO protection to have high inductance values, it's necessary to use a material with good magnetic conductivity. The rings' ability to respond to high frequencies is also a crucial factor in their performance. If the ferrite ring has a weak high frequency response, it can result in a low equivalent resistance, which can lead to a high level of failure and poor VFTO protection. It is essential to select the ferrite material that has high magnetic conductivity and a good high frequency response to achieve optimal VFTO protection. The ferrite rings should be designed and selected based on the specific requirements of the application, considering the material properties, geometry, and configuration of the ring and busbar. When the equivalent resistance of the ferrite ring is zero, it provides negligible resistance to the traveling wave and therefore no mitigation effect on VFTOs. In this case, even if the value of inductance is high, it will not be effective in reducing the amplitude of the VFTOs.

On the other hand, if the equivalent resistance is extremely high or approaches infinity, the ferrite ring will only contribute to the inductance of the VFTOs. This will limit the sharpness of the VFTOs, but their amplitude will remain unchanged. It is important to note that for effective VFTO protection, the ferrite ring should have both a high inductance value and a significant equivalent resistance. This ensures that the amplitude of the VFTOs is reduced while the steepness is restricted.

By selecting an appropriate resistance value, the ferrite ring can absorb energy from traveling waves or voltage transients. A proper balance of inductance and resistance can lead to a substantial reduction in the energy of traveling waves and effectively dampen voltage transients.

The magnetic saturation of the ferrite material used in the ferrite ring is an important factor to consider when designing for VFTO protection. When the ferrite ring approaches capacity, its corresponding inductance L recedes, which reduces its effectiveness in mitigating VFTOs. Therefore, the ferrite material needs to be carefully selected to ensure that the ferrite ring does not saturate when acted upon by passing waves with high current levels, typically in the kilo-amperes range. The best VFTO protection can be achieved by selecting ferrite material that have high magnetic conductivity, good high frequency response, balanced inductance and resistance values and minimal magnetic saturation when acted upon by high current level.

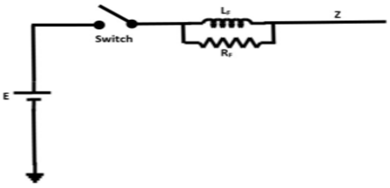


Fig 8. Equivalent circuit of Ferrite Rings

That is an interesting approach to evaluating the effectiveness of ferrite rings in minimizing voltage transients or VFTOs. By measuring the efficiency of the ferrite rings in four ultrahigh voltage rated GIS (Gas Insulated Switchgear) equipped substations, you can gather a significant amount of data and draw useful conclusions about the performance of the ferrite rings under different conditions. This type of testing can provide valuable information about how well the ferrite rings are able to mitigate VFTOs and how to optimize their design and implementation for maximum effectiveness.

4.4. Suppression of VFTOs by Nanocrystalline Rings

Nanocrystalline materials, such as alloys of silicon, iron, and boron, can be used to suppress fast voltage transients in GIS switchgear by wrapping them around the inner conductor. These materials can be transformed into very thin ribbons using rapid hardening technology and then shaped into rings. Heat treatment at high temperatures can then be used to create nanocrystalline structures the materials have fine grains dispersed within an amorphous residual phase, with grain sizes that can vary from 10 to 40 nanometers. Additionally, the properties of these materials can be adjusted during heat treatment through the application of external magnetic fields.

Nanocrystalline materials have a maximum magnetic field saturation limit. In gas insulated substations (GIS), the magnetic field strength exceeds the saturation limit due to the high current flow in the inner conductors. Consequently, there is no energy loss in the low frequency range as the ferrite rings are magnetically saturated. However, energy loss can occur at higher frequencies, such as those in the hundreds of MHz range, due to voltage transients. This is where the nanocrystalline rings can effectively suppress fast voltage transients (VFTO) by absorbing the energy from the transients.

When nanocrystalline rings are placed around the inner conductor in gas-insulated switchgear (GIS), various types of losses can contribute to the damping of voltage transients. One of these losses is hysteresis loss, which results from the changing alignment of magnetic domains in response to the alternating magnetic field of the nanocrystalline system. This rotational energy of the magnetic domains is then transformed into thermal energy. The rotating energy of the magnetic domains is converted into thermal energy, which dissipates as heat. Additionally, eddy current loss occurs due to the induced currents flowing within the nanocrystalline rings. The third type of loss is the residual loss that occurs due to the amorphous phase present in the material. Overall, the combination of these losses helps to effectively damp voltage transients in GIS.

The small losses that occur in nanocrystalline rings, such as hysteresis and residual losses, are not significant and do not contribute greatly to transient damping. The primary mechanism for damping voltage transients in GIS using nanocrystalline rings is through eddy current loss. The Voltage transients around the inner conductor in the direction of the winding of the nanocrystalline ring generate a rapidly rotating magnetic field.

The interaction between this magnetic field and the magnetic field of the nanocrystalline rings generates steep field variations, which induces eddy currents. The loss of power caused by these eddy currents effectively reduces voltage transients and this suppression increases with frequency. So, the eddy current loss is the main loss that contributes to damping voltage transients.

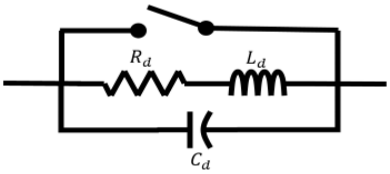


Fig 9. Equivalent Circuit of nanocrystalline ring

5. Simulation Results

Simulation using MATLAB/SIMULINK is performed on 1500KV substation shown in figure 5 to check performance of four suppression techniques to mitigate very fast transient overvoltage. Substation design for 1500KV presented in [17] is adopted and each component of the substation are modelled using their behavior to high frequency transients as described in section 2. Switching condition is applied on a disconnector switch and transients generated at different places of the substation are presented here for four suppression techniques.

5.1. Mitigation of VFTOs in 1500 KV GIS by Resistance

The results of voltage transients for a 1500 KV substation are presented in this study. Figure 5 shows a single line diagram was created to represent a 1500 KV substation, which was modeled and simulated with and without the incorporation of resistance as a mitigation device. The study presents the VFTOs (very fast transient overvoltage) that occur at the impact of the switching operation of CB1 disconnector switch on the connection point of switches (CB1-CB15) in a 1500 KV substation was analyzed, specifically without the use of any mitigation device.

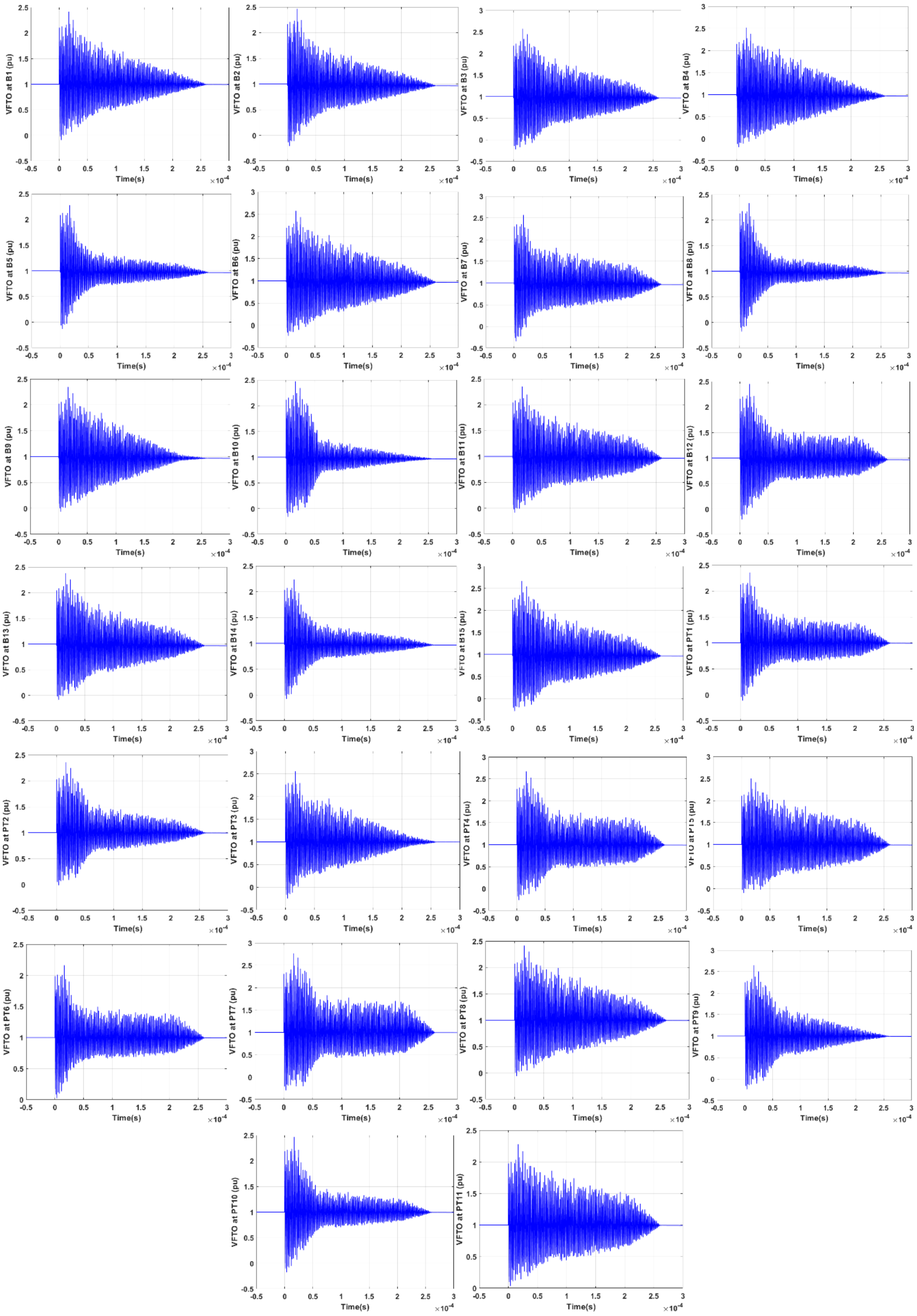


Fig 10. Without suppressive methods at the CB1 to CB15 and PT1 to PT11 of the 1500 KV system results in the presence of VFTOs.

The study presents the VFTOs (very fast transient overvoltage) that occur at the effect of the switching operation of CB1 disconnector switch on the connection point of switches (CB1-CB15) in a 1500 KV substation was studied, but this time with the inclusion of resistance as a suppressive method.

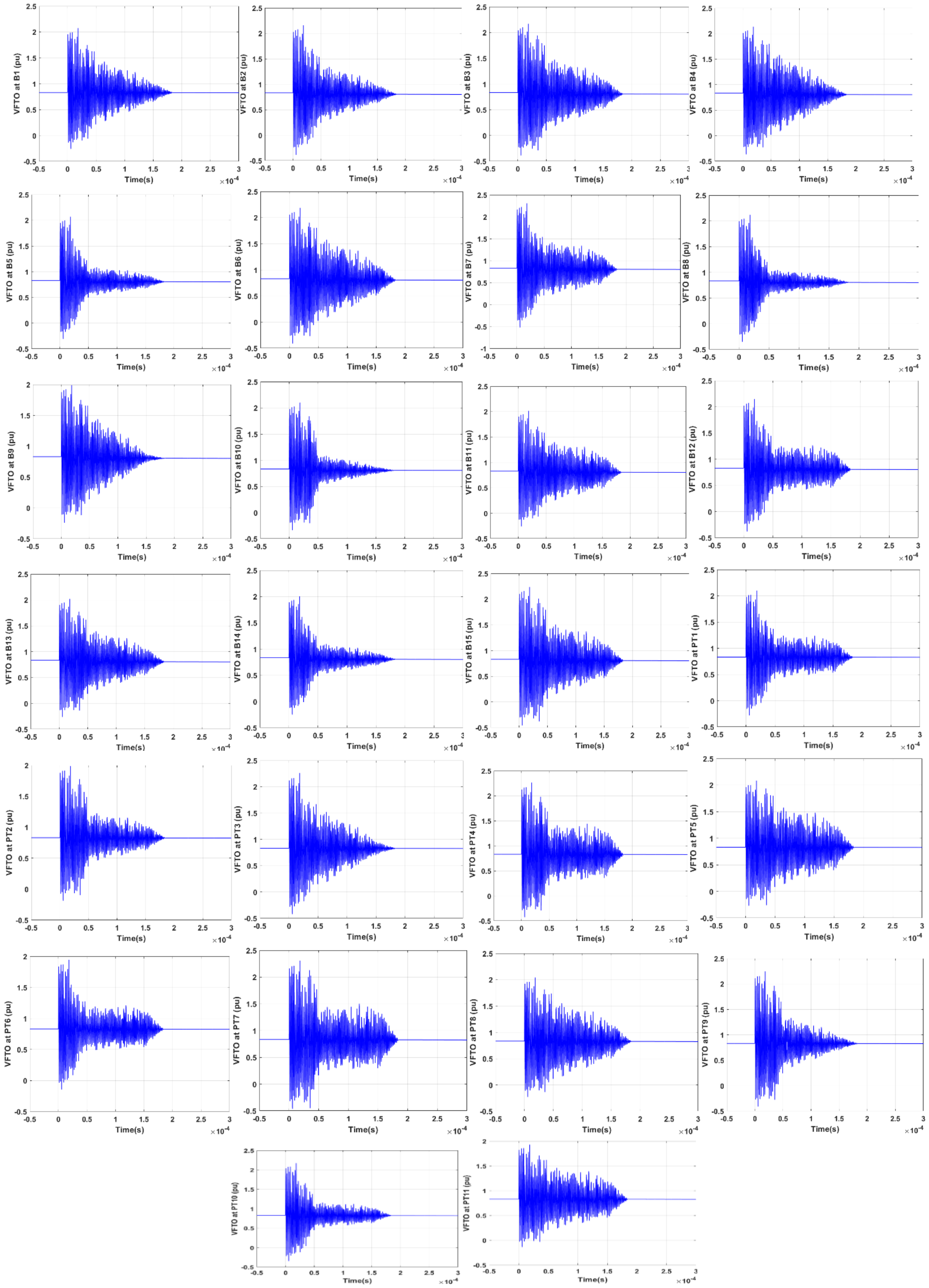


Fig 11. At the 1500 KV substation, the CB1 to CB15 and PT1 to PT11 have VFTOs, which are reduced using resistance.

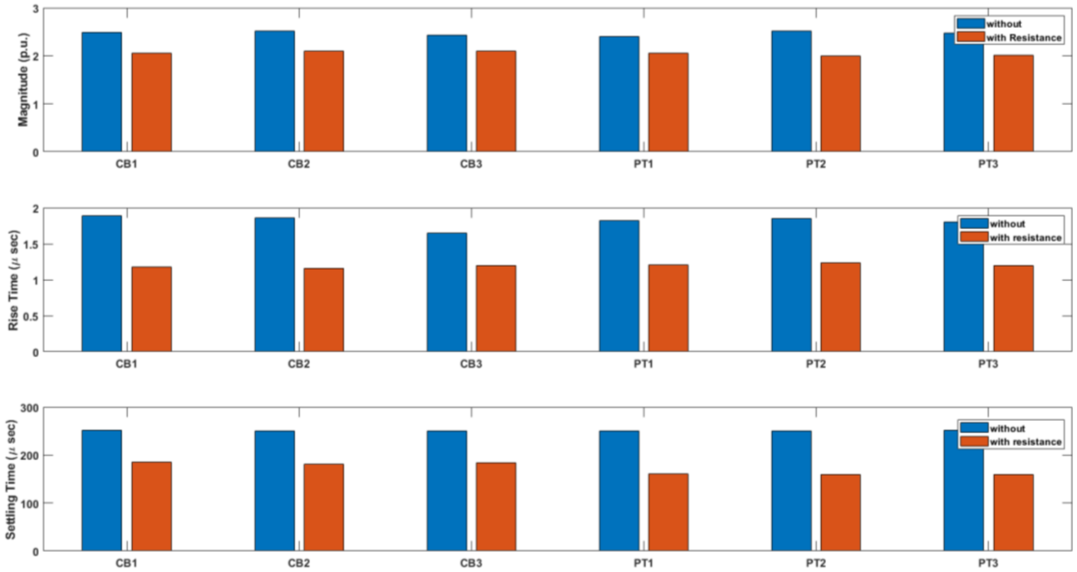


Figure 12. Performance of Resistance as suppressive method

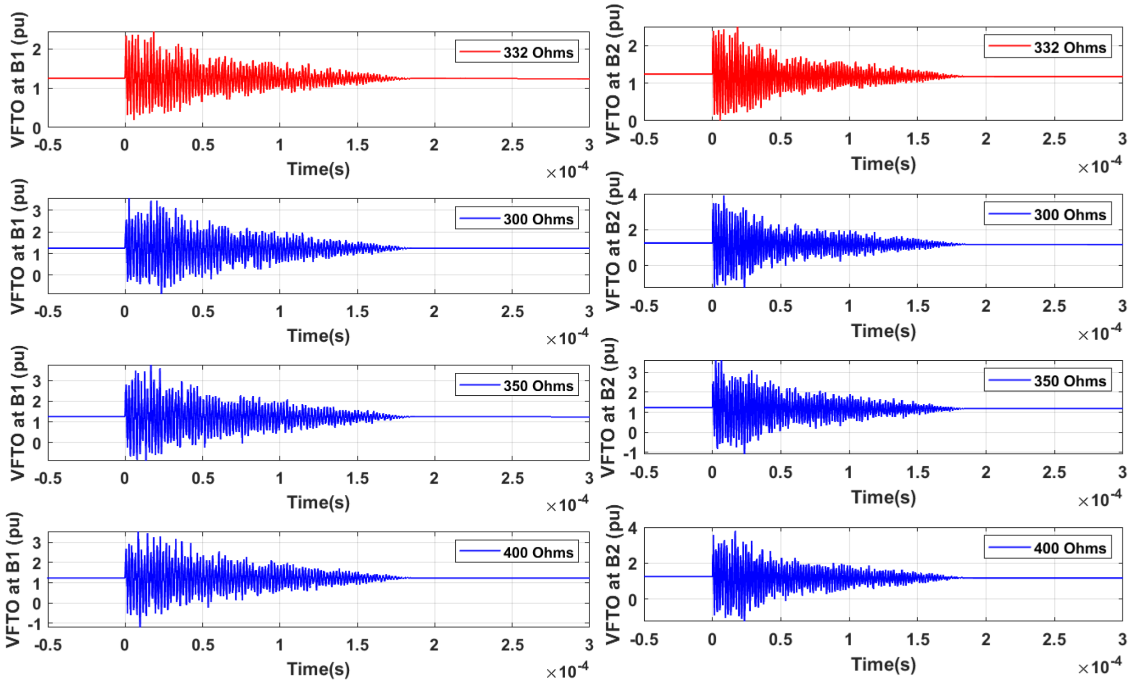


Figure 13 the behavior of the voltage fast transient's overvoltage (VFTOs) at the B1 and B2 locations of the substation was analyzed for four different resistance values.

5.2. Suppression of VFTOs in 1500 KV GIS by RC Filter

Here are the results of the analysis of voltage transients in a 1500 KV substation when using an RC filter as a mitigation device. The optimal values of 296 Ohms for resistance and 3.86 Farads for capacitance were determined through a study that evaluated the performance of the modeled 1500 KV substation system with various RC filter combinations for CB1-CB3 and PT1-PT3, both with resistance and with an RC filter. The results of this analysis, including the magnitudes of the VFTOs and their settling and rise times, are presented in a tabulated format.

Figure 16 displays the evaluation of the proposed resistance and capacitance values by showing the very fast transient overvoltage (VFTOs) at the B1 and B2 locations for four different RC filter combinations. The study results showed that the use of an RC filter instead of resistance as a mitigating device in the disconnector switch led to a 16% reduction in voltage transient magnitudes and a 40-50 second reduction in settling time. The peak magnitudes of VFTOs ranged from 2.01-2.1 p.u. with resistance and from 1.72-1.9 p.u. with the RC filter.

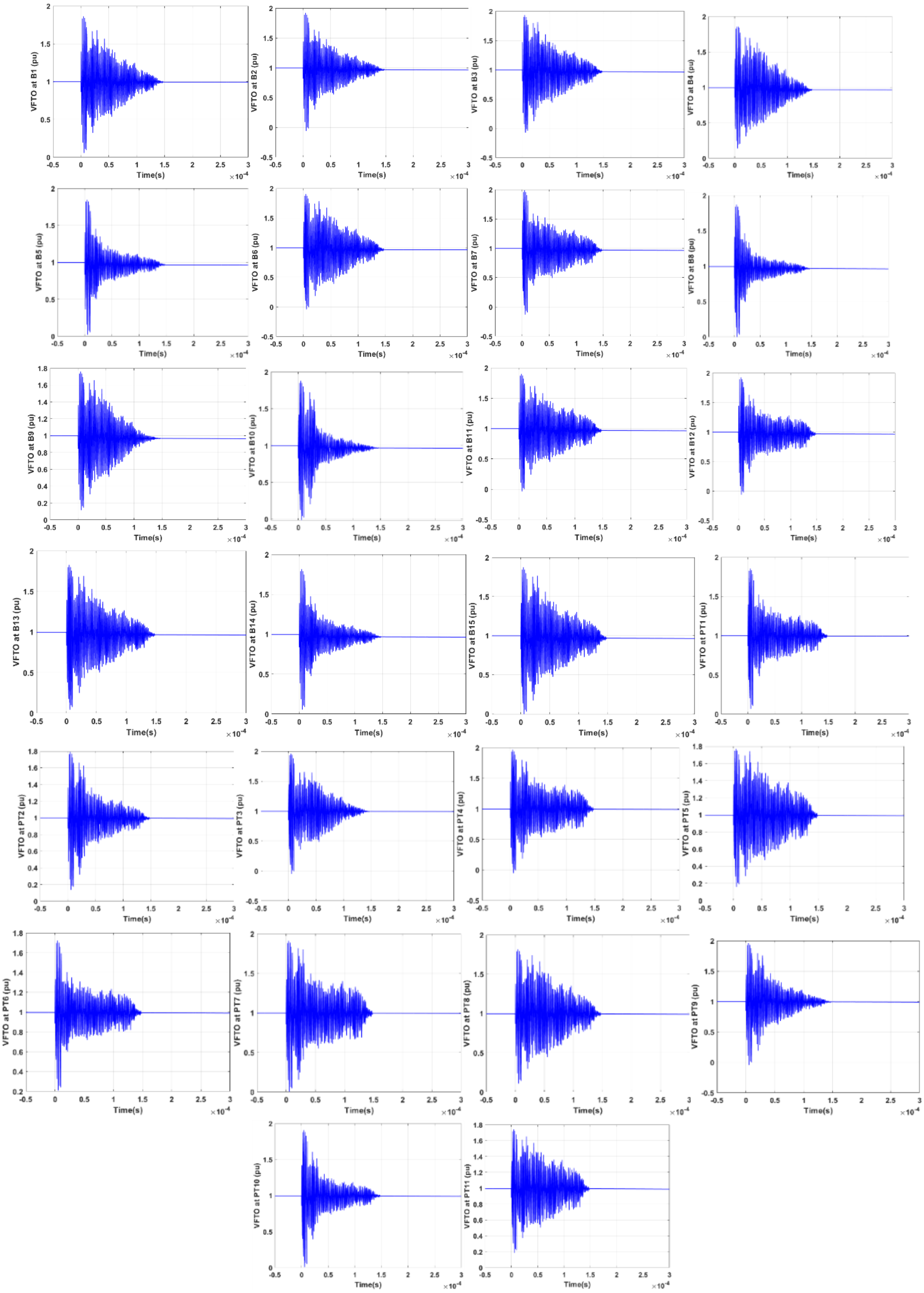


Figure 14 the VFTOs at the CB1 to CB15 switches and the PT1 to PT11 of the 1500 KV substation, which are suppressed by means of an RC Filter.

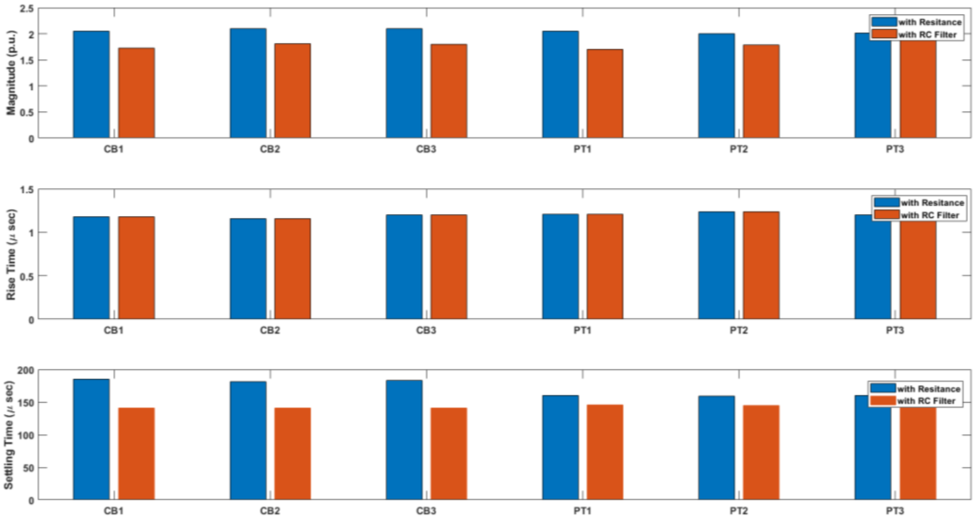


Figure 15. Performance of RC Filter as suppressive method

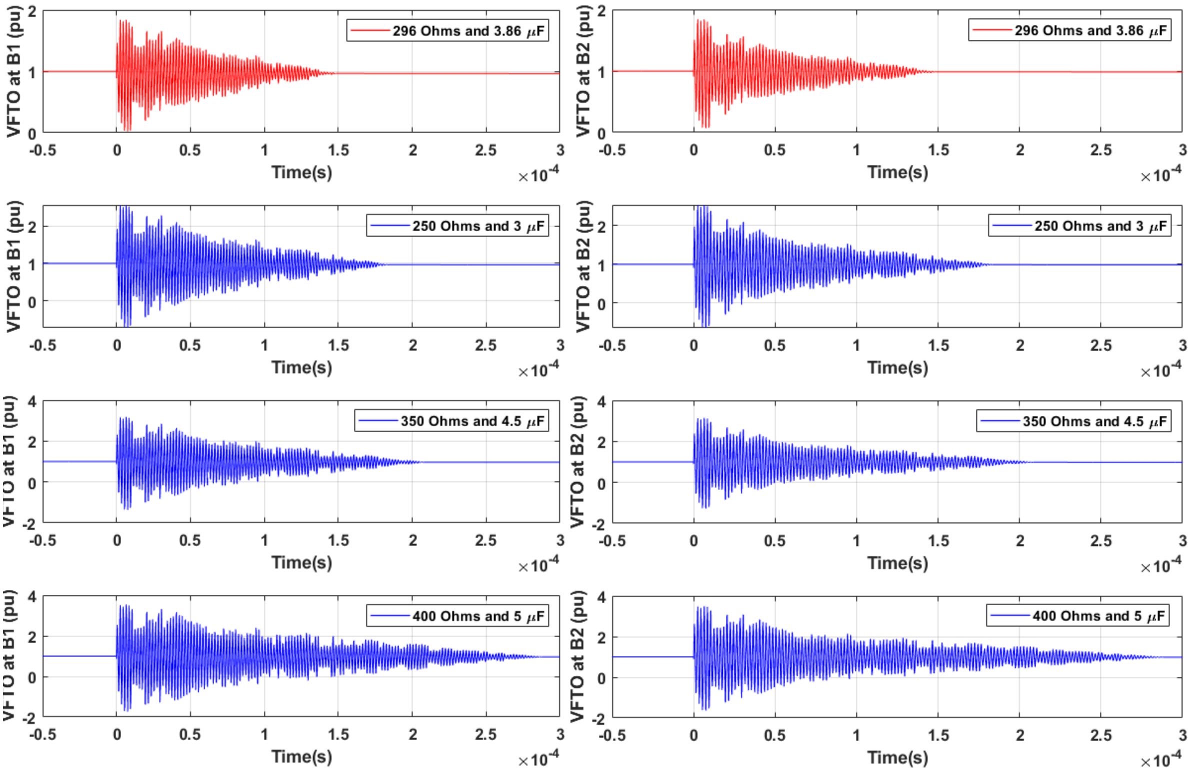
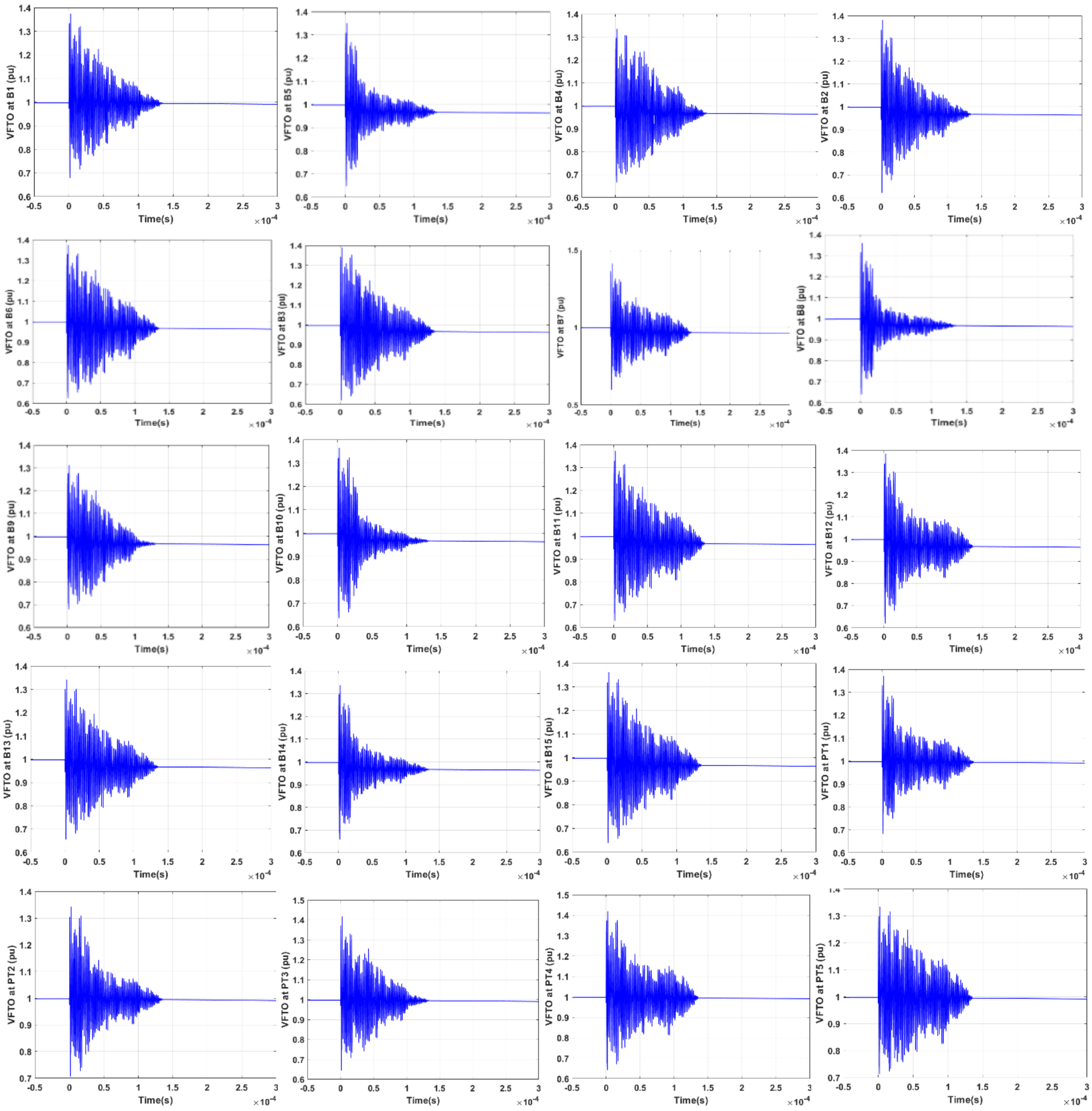


Figure 16 the voltage transient overvoltage (VFTOs) at points B1 and B2 in the substation for four different combinations of resistance and capacitance values, which were used as RC Filter mitigating devices.

5.3. Suppression of VFTOs in 1500 KV GIS by Ferrite Rings

The study modeled the 1500 KV substation's equivalent circuit and simulated switching events to evaluate the effect of attaching ferrite rings as mitigating devices to each disconnector switch on voltage transients. The study aimed to improve the performance of ferrite rings as voltage transient mitigation devices in a 1500 KV substation. The study conducted an analysis of the equivalent circuit and switching events to observe the voltage transients. The optimal values of resistance and inductance were determined by examining the impact of different ferrite ring values on the VFTOs, which resulted in 128 ohms of resistance and 3.68 Farads of inductance. The study presents the results of the magnitude, settling time, and rise time of the VFTOs for CB1-CB3 and PT1-PT3 both with the ferrite rings and an RC filter.

Figure 19 illustrates the VFTOs (very fast transient overvoltage's) at the B1 and B2 locations for four unique ferrite rings, to evaluate the effectiveness of the proposed resistance and inductance values. The study found that by inserting ferrite rings with optimized standards, the study found that the use of ferrite rings as a voltage transient mitigation device led to a reduction of 21% in the magnitudes of voltage transients and a decrease of 30-40 seconds in the settling times. Furthermore, the peak magnitudes of VFTOs were compared between using RC filters and using ferrite rings, with the results showing that the peak magnitudes were reduced from 1.72-1.9 per unit with RC filters to 1.35-1.38 per unit with ferrite rings.



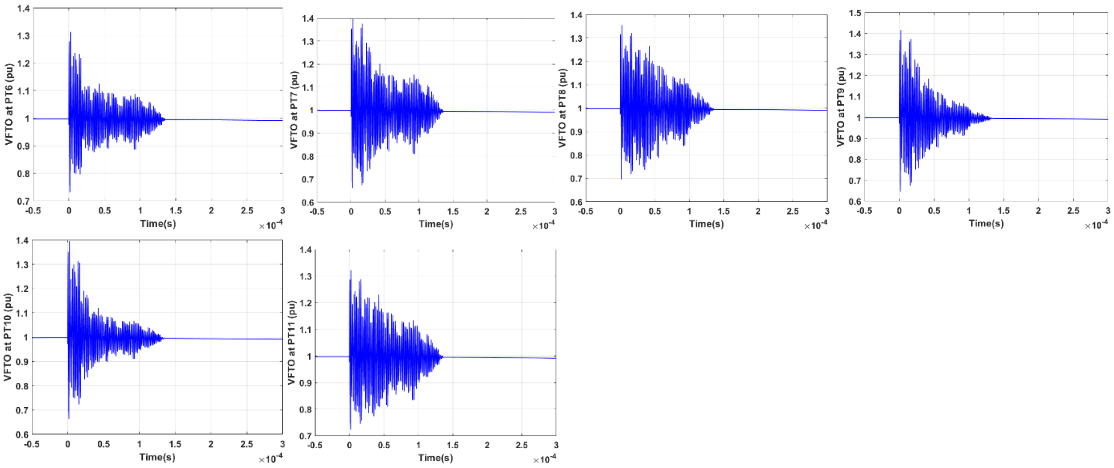


Figure 17 the VFTOs at the CB1 to CB15 and PT1 to PT11 of the 1500 KV substation, which are suppressive using Ferrite Rings as the suppressive method.

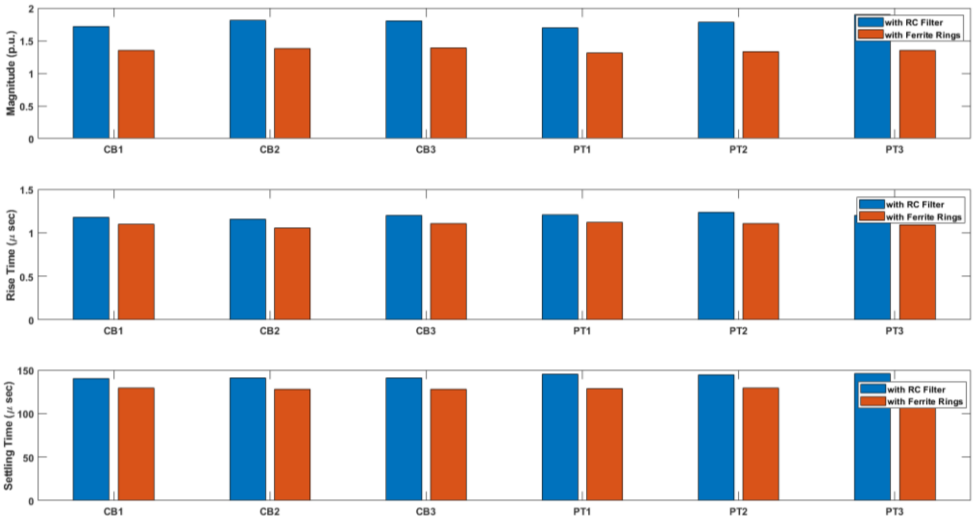


Figure 18. **Performance of Ferrite Rings as suppressive method**

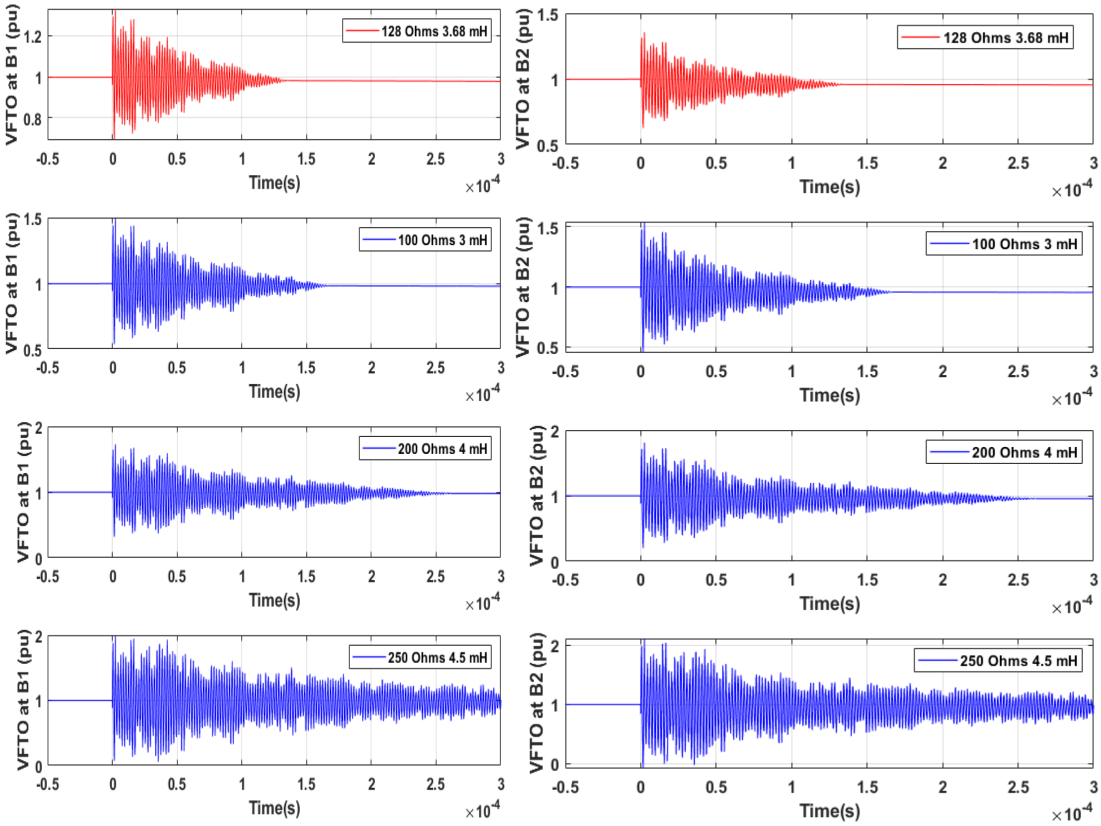


Figure 19 illustrates the VFTO's at the B1 and B2 locations of the substation for four different combinations of resistor and inductor values in the Ferrite Rings.

5.4. suppressive of VFTOs in 1500 KV GIS by NanocrystallineRings

The study assesses the impact of high voltage oscillations on a 1500 KV gas-insulated substation and its components by modeling and simulating the behavior during switch disconnect events. The study evaluates the effect of very fast transient overvoltage (VFTOs) on various points in the substation by using Nanocrystalline rings as voltage transient mitigation devices. The study determined optimal values of 85 Ohms of resistance, 5.89 millihenries of inductance and 4.96 Farads of capacitance by analyzing the behavior of a 1500 KV gas-insulated substation during high voltage oscillations, evaluating the effect of very fast transient overvoltage (VFTOs) on different points of the substation by using Nanocrystalline as a mitigating device.

The effectiveness of the proposed resistance, inductance, and capacitance values is evaluated through a representation of the voltage transients at the B1 and B2 locations in the 1500 KV GIS substation caused by four different parameters of the nanocrystalline system, shown in Figure 22. The study determined that using nanocrystalline instead of Ferrite Rings as a voltage transient mitigation system in a disconnector switch in a 1500 KV GIS substation significantly reduced the magnitude of voltage transients by 30%. Additionally, the settling time was decreased by 40-50 seconds. The peak magnitude of VFTOs was found to vary between 1.1-1.165 per unit when using nanocrystalline, a decrease from the 1.31-1.38 per unit range with Ferrite Rings.

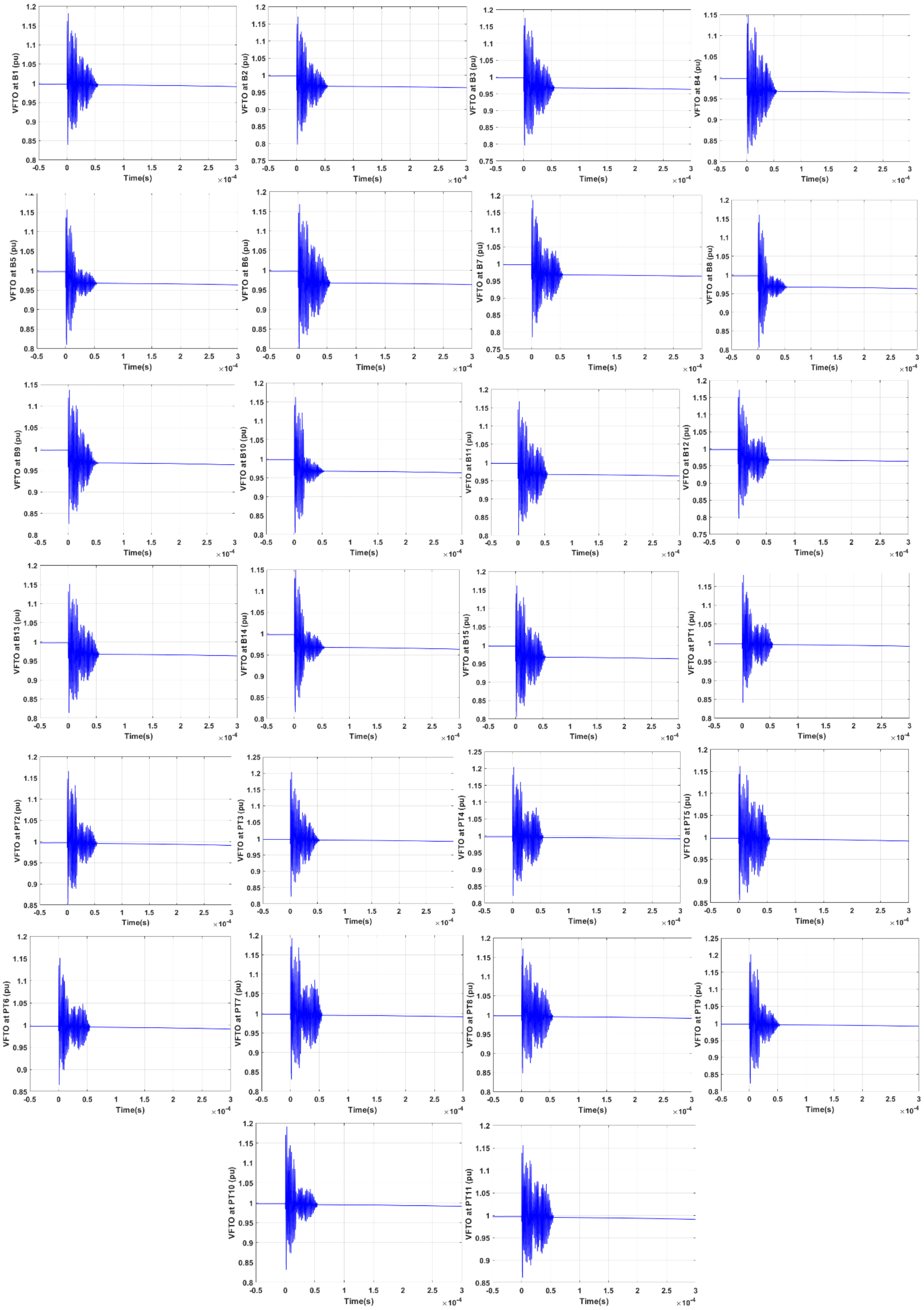


Figure 20. The VFTOs at the CB1 to CB15 and PT1 to PT11 of the 1500 KV substation that are suppressed using Nanocrystalline as the suppressive method.

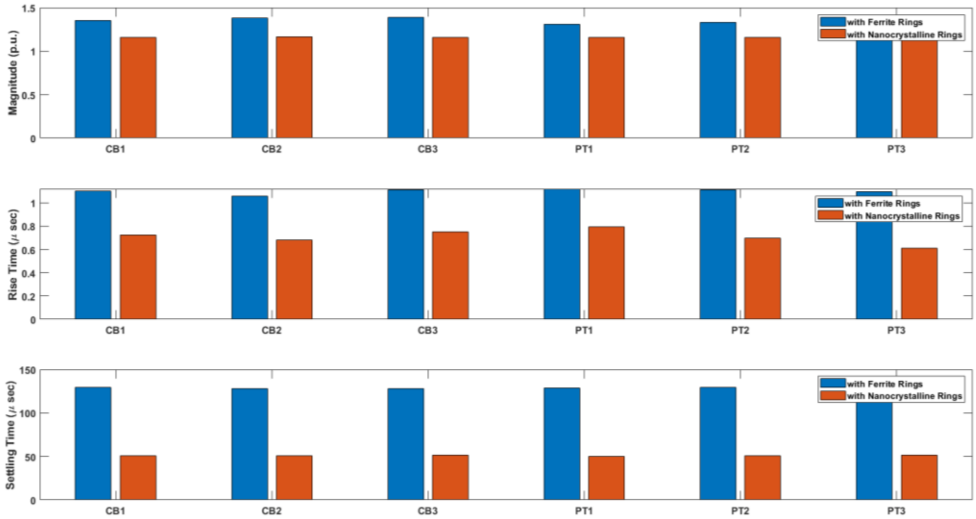


Figure 21. Performance of Nanocrystalline rings as suppressive method.

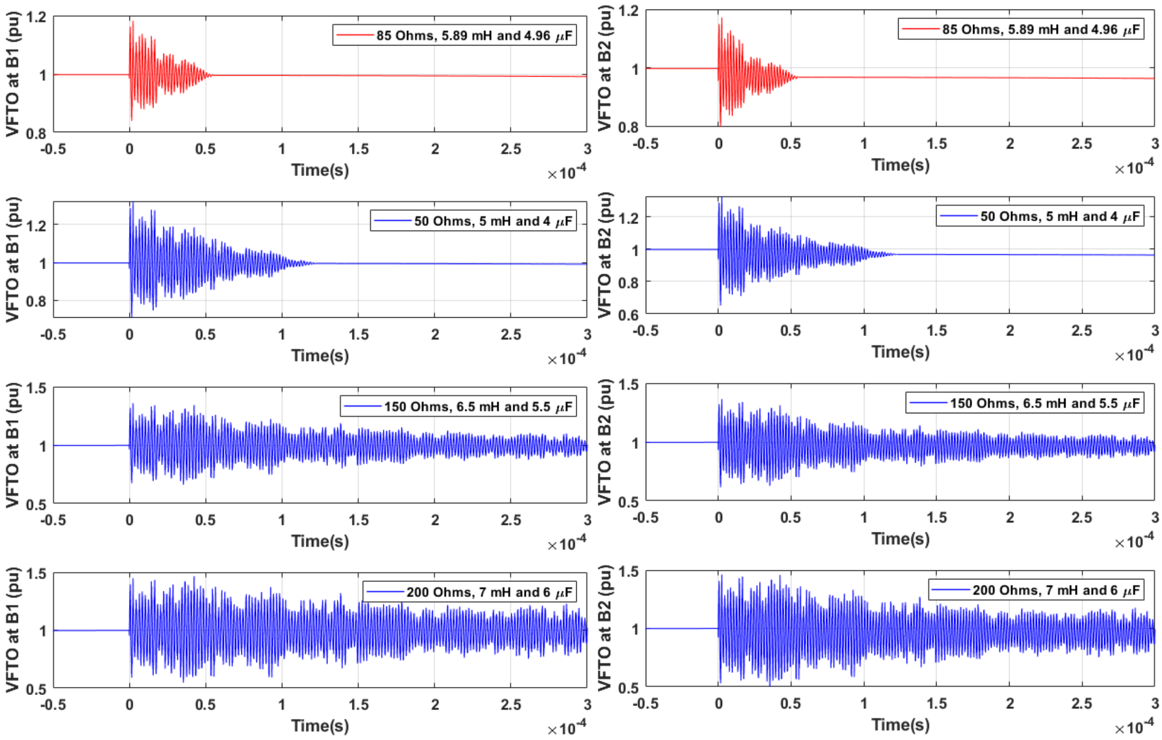


Figure 22. the voltage transients (VFTOs) at the B1 and B2 locations of the 1500 KV substation for four different configurations of resistance, inductance, and capacitance in the Nanocrystalline device.

6.Conclusion

VFTOs are significant concern in extra high voltage gas insulated substations where the ratio between impulse withstand voltage and fundamental rated voltage is low. To minimize their impact on other equipment in the substation, suppression techniques must be implemented. The paper presents four techniques for suppressing VFTOs in a 1500kilovolt extra high voltage substation and compares their effectiveness about maximum value, rise time, then settling time of oscillations. The optimization of the parameter values for these techniques was achieved by conducting multiple simulations on a 1500KV substation. The substation components were modeled based on their behavior for high frequency oscillations. The simulation results and comparisons showed that the use of nanocrystalline rings as suppressive method is more effective than the other three techniques studied.

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