Journal of Harbin Engineering University
ISSN: 1006-7043

Vol 44 No. 5
May 2023

Selection of Optimal Mitigation Technique to Suppress the VFTOS in 765KV UHV GIS Substations

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Abstract: Suppression of VFTOs by using four different devices in 765KV UHV GIS substation is presented in this paper. Restrike and prestrike occurs repeatedly while operating a disconnector switch into ON state or into OFF state. In GIS, travelling waves propagate through switchgear, due to the rapid time for the voltage breakdown. Dielectric strength of components of substation reduces with this high-frequency transients. As a result of the interface between transient over voltages and enclosures, transient ground potential rise or transient enclosure voltages appear for a very short duration. This creates flashovers to nearby grounded items. It is necessary to reduce VFTOs in GIS based EHV substation. Four techniques are presented to suppress VFTOs in a 765KV UHV substation and results are compared in terms of peak value, rise time and settling time of oscillations. Simulation is performed on 765KV substation using MATLAB/SIMULINK.

1. Introduction

Due to reduced size, less required space, pollution less, less maintenance, and increased reliability Gas Insulated Substations are gaining popularity in recent times. Because of its arc quenching capability and high insulation property, SF6 is the ideal choice for gas insulated switchgear [1]. Since 1968, in which GIS is introduced, this technology is enhancing the reliability and a increasing the lifetime of substation equipment. High voltage parts of the GIS do not affect directly by impact of the environment changes because of the protection by SF6 gas. The internal of the GIS is under very persistent and dry conditions [2].

Despite of these advantages, main problem with GIS is very fast transient over voltages (VFTOs) during switching operation of the disconnector switches or circuit breakers. Switching of the equipment in GIS increases or decreases the voltage instantaneously at the contacts and at the components of the substation [3]. Rise time of these transient voltages is in the range of 10 to 100 ns, and magnitudes may reach 2-2.5 pu. These transients are accompanied by the oscillations having frequencies in the range of 50 kHz to 100 MHz. Travelling waves propagate through gas insulated switchgear, between contacts of the switching devices and other components [4]. This can lead to harm the insulation of internal busbar and transformer, that effect the functioning dependability of GIS, accelerate aging of transformer insulation and decrease transformer life. Transient currents propagating through GIS bus due to transient over voltages increases electromagnetic interference (EMI) [5].

Mitigation of the transient over voltages is necessary for the protection of equipment of substation and to reduce EMI. Analysis and Suppression of transients is gaining popularity in researchers in recent years especially for extra high voltage (EHV) and ultra-high voltage substations [6]. For these range of voltages maximum value of transients may exceed insulation withstand voltage, and hence it is necessary to increase insulation level. It indicates that transient over voltages generated during the switching operations should be correctly examined and should be mitigated [7].

Numerous approaches for VFTO mitigation are being investigated in recent times by scholars. The most recent summary of mitigation techniques for transient over voltages are presented in papers [8], [9]. Mitigation of VFTOs in 245KV GIS was presented in [10]. Using High frequency resonators [8], magnetic material [9], capacitors [10] to attenuate VFTOs presented in literature. A novel magnetic material for suppression of VFTOs is presented in [11], whose contribution depends on the energy dissipation in magnetic materials. GIS with surge arresters to mitigate VFTOs is presented in [12]. A new arrangement for the disconnector switch contact system is presented in [13]. Electromagnetic resonator with flashing element fitted to source of VFTOs is presented in [14].

In this paper four mitigation techniques for 765KV rated gas insulated substation to reduce VFTOs are proposed and compared in terms of rise time, peak value and mitigation time. The mitigation techniques have been investigated at disconnector switches if 750KV GIS. Each component of the substation is modelled using their equivalent circuit and their behavior for high frequency transients. Substation design and modelling of the components are explained in section 2. Four mitigation techniques are explained in section 3. Simulation results using MATLAB/SIMULINK are presented and four techniques are compared in section 4.

1. Gas Insulated Substation

A Gas Insulated Substation consists of buses, switchgear, and related equipment which are accumulated in a metallic casing and insulated using gas as the medium. Over five decades GIS are important equipment for the transmission system and is used worldwide. In traditional air-insulated substations (AIS), the air is used as an insulator medium, and in gas-insulated substations, SF6 (Sulphur hexafluoride) is used as an insulator. The dielectric strength of SF6 gas is 2 to 3 times that of air at standard barometric pressure. This gas is nonflammable, inodorous, innocuous, and passive. Less maintenance, safe environment feasibility, less space occupation, and working safety are some of the advantages of GIS over AIS.

During the switching of the equipment in GIS Very Fast Transient Over voltages (VFTOs) occur which breakdown the insulation medium SF6 and which effect other equipment. These transient over voltages will reach the peak value within 0.1 microseconds and consists of superimposed oscillations with a frequency range of 50 kHz to 120 MHz. Within very less time VFTOs reach a peak value of 2-2.5pu. For regular disconnecting condition, VFTOs increase from 1pu and may reach 3pu while propagating away from the switch. During lightning, over voltages may reach 7pu. To protect the equipment from this much of voltage, insulation of the system can be designed to handle basic insulation voltage level (BIL). For low to high voltage substations, VFTOs are below the BIL and hence insulation can able to handle these transient voltages. But for EHV substations, increase in system level voltage reduces BIL and if range of VFTOs reach basic insulation voltage level, the insulation and the equipment will be affected during switching conditions. Recurrent incidences of VFTOs will contribute to the aging of insulation. For EHV substations above 345kV care has to be taken to protect the equipment and eliminate the system's shutdown.

According to Toepler, during incidence of breakdown of a gas gap, time for voltage to drop from 90% to 10% is in the range of few nanoseconds and during this time the potential of electrodes equalizes. The spark resistance which is inversely proportional to the function of time reduces from very high value (>>10^6 Ohm) to a very low value (≅4 Ohm). By relating this with the VFTO, according to Toepler spark resistance can be defined as

$$R_t = l\frac{k_t}{\int_0^t i dt}$$

k_t is the Toepler's constant which is equal to $0.5X10^{-2}$Vs/m

As switching operation of switching devices like disconnector switches and circuit breakers is a regular event in high voltage substations, the occurrence of VFTOs collapses the voltage in Gas Insulated Switchgear. Propagation of transients of the traveling wave is in either direction from the source. At the instant of inter-contact collapse, disconnector voltage which is at the load side alters from V_L to

$$V_L + \frac{(V_S - V_L)}{(Z_S + Z_L)} \times Z_L$$

And the voltage of the disconnector switch which is at the source side alters from V_S to

$$V_S - \frac{(V_S - V_L)}{(Z_S + Z_L)} \times Z_S$$

Z_L surge impedance or characteristic impedance at the load side at a voltage of V_L, Z_S surge impedance or characteristic impedance at the source side at a voltage of V_L. The initial amplitude of these voltage changes is subject to the voltage δu across the disconnector switch soon after the restrike. Let for example, for an equal surge impedance of load and source side and for a grounded load V_S reduces from 1 pu to 0.5 pu and V_L increases from 0 to 0.5 pu. For a 750 KV GIS change in voltage is 375KV within 3ns which means the rate of change of voltage is 125MV/µs.

During the opening of a disconnector switch, at the instant of separation, both the contacts of the switch will have the same value. After the separation initializes, the voltage of the contact at the source side is with power frequency, and the voltage of the contact at the load side reduces. When the difference between these two equates to the dielectric strength of the gap between the contacts, a breakdown occurs and it generates a spark that connects both contacts electrically. Due to this, the voltage at the contact of the load side increases instantly and the spark quenches. As the switch-opening process is ongoing, the gap between contacts increases, and hence dielectric strength level also changes. When the difference between the voltages at both the contacts reaches the level of dielectric strength, restrike arises. This process continues until the gap among the contacts is large enough. Restrike occurs in the disconnector switch several times during the closing or opening process of the switch. Voltages with high amplitudes are generated during prestrike and restrike when traveling waves are reflected and refracted. Similarly, it was detected that more disconnector-actuated transients arise throughout the opening as a consequence of the arithmetic difference in the commonly organized nature of the disconnector switch process.

The disadvantages related to the VFTOs are as follows:

1. Electric discharge from the DS contacts to the earth
2. As a result of the interaction between transient overvoltages and enclosures, transient ground potential rise or transient enclosure voltages appear for a very short duration. This creates flashovers to nearby grounded items.
3. Dielectric strength of components of substation reduces with high-frequency transients.
4. Power transformers, instruments other substation equipment is affected by aging
5. Sensitive electronic circuits are affected by EMI of high-frequency transient overvoltages.
6. For the above reasons, VFTOs are to be considered while designing the insulation level for the equipment of the substation and hence increase the cost.

Hence it is necessary to mitigate the VFTOs to protect high-voltage apparatus in gas-insulated switchgear from high-voltage stress and corrosion. In this paper mitigation of VFTOs in a 765KV substation using four mitigation techniques is presented and compared through simulation. Components or equipment of the substation are modeled using their internal process and their lumped elements.

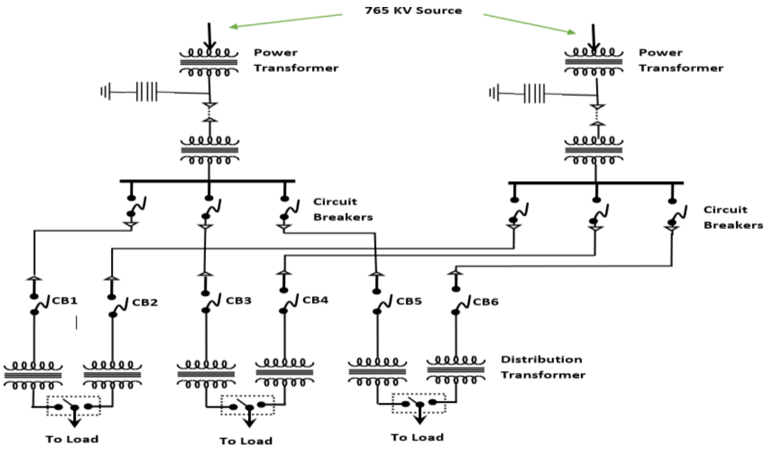


Fig 1. 765kV substation single line diagram

2. GIS Components Modelling of 765KV substation

Single line diagram of 765KV substation presented in [15] is shown in figure 1. Double input feeders fed by 765KV line connected to two power transformers to step down the voltage to 345KV. Again, the voltages are stepped down to 138KV with two step-down transformers and then fed to the load through distribution transformers and circuit breakers, and disconnector switches. Six disconnector switches can be operated to study the magnitude of VFTOs and the percentage of mitigation by using the proposed techniques.

Due to propagating pattern of transients, components of the GIS substation can be exhibited as lumped elements. When the transformer is exposed to the VFTOs, transformer winding has a major impact on their electrical characteristics. The uncertainty of voltage dispersal in the transformer due to VFTOs need to be justified in modeling the power transformer. For high-frequency transient overvoltages, transformers behave like a capacitive network. Hence transformer can be modeled as series shunt capacitance to analyze VFTOs. Surge impedance, propagation velocity, length of the winding, formative time, and series and shunt capacitance between the winding turns and the coils are considered to calculate the values of inductance and capacitance which represents the power transformer in substation modeling.

$$L_{Tran} = \frac{\mu_o}{2\pi}\left[\log\frac{2l}{R} - 1\right]$$

$$C_{Tran} = \epsilon_o \epsilon_r \left(\frac{Wl}{d}\right)$$

For better simulation presentation, the parameters of the transformer can be calculated depending on the magnitude and frequency of transient over voltages,

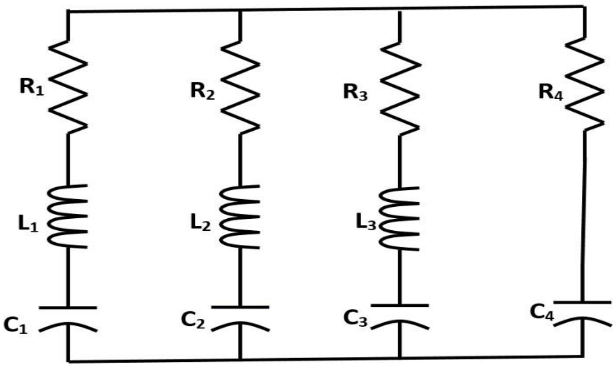


Fig 2. Power Transformer Model

A disconnector switch can be modeled for the simulation by considering its behavior during the open and closed conditions. Due to the movement of the contacts during switching on and off several pre and re-strikes happen. When contacts are closing, the charge between them increases and hence flickering happens. A closed disconnector switch can be modeled as a lossless transmission line. An opened disconnector switch can be modeled as a capacitor. The equivalent circuit of the disconnector switch to analyze VFTOs is depicted in figure 3.

An exponentially decaying resistance can be used to reflect the spark between contacts.

$$\boldsymbol{R = R_o e^{\left(\frac{-t}{\tau}\right)}}$$

R_{spark} is spark resistance,
R_0 is equal to 108Ω,
t is formative time,
r is time constant in range of 0.5 nano seconds.

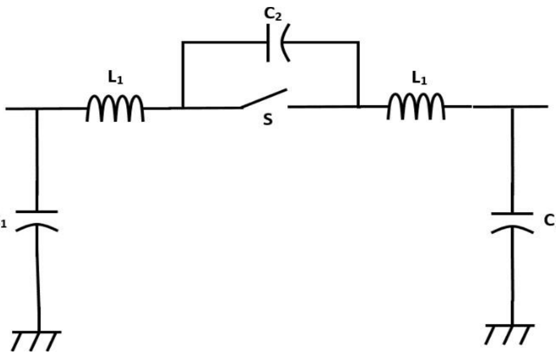


Fig 3. Disconnector Switch model

The circuit breaker in the closed position can be represented as a lossless transmission line and in the opened state as a series of capacitors with internal resistances. The equivalent circuit of the circuit breaker to analyze VFTOs is depicted in figure 4.

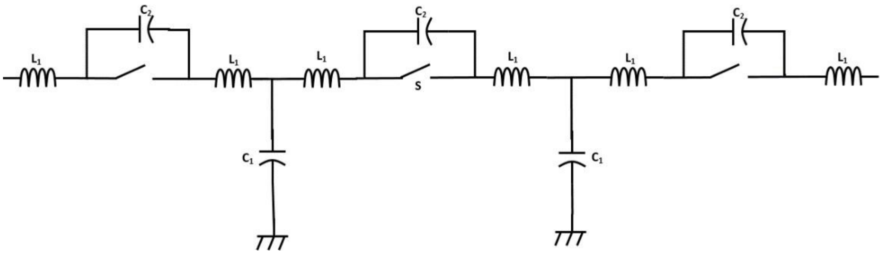


Fig 4. Circuit Breaker model

3. Suppression of VFTOs

a. Using Resistance

By inserting a resistor in series with the disconnector contacts, increases the opposition to the propagation of travelling wave which is oscillating due to switching operation. The rate of change of magnitude and frequency of refraction and retraction reduces due to increased resistance in travelling path of the oscillations and hence VFTOs are mitigated. The magnitude of the resistor depends on peak value, rise time and frequency of over voltages.

If the maximum value of VFTO surpasses the insulation level in an ultra-high voltage GIS device, it is hard to design and conquer VFTO for insulation management. The use of a damping resistor to suppress fast transients is a well-proven method. The proportion of mitigation is calculated by the resistance value. When spinning on a disconnector switch, resistance arc or spark between contacts may exists.

$\boldsymbol{R_{spark}} = \boldsymbol{R_0} \boldsymbol{e^{-t/c}} + \boldsymbol{R_f}$ (10)

$\boldsymbol{R_0}$ is equal to 108Ω,

$\boldsymbol{R_f}$ is the fixed resistance in the range of 0.5 Ω.

More spark resistance, decreases leakage current over spark across contacts. Hence frequency of travelling wave's reflection and refraction decrease and will reduce peak value of VFTOs and rise time also reduces.

b. Using RC Filter

RC filters are used to protect the loads from High-frequency oscillations at distribution side or consumer side. In transmission, stations, RC filters are used to protect circuit breakers from over voltages induced due to arcing. Oscillations with high frequency are filtered by capacitor and dissipated by resistance. Capacitor offer low resistance path to the high frequency oscillations because of frequency dependent. By redirecting very high voltage transients, an RC filter with disconnector switch suppresses them. The frequency and magnitude of voltage transients regulate the magnitude of resistance and capacitance in an RC filter. Figure 5 depicts a typical RC filter interface structure. The reactance given by capacitance to high frequency oscillations is inversely proportional to the frequency of the oscillations. As a result, high frequency oscillations are possible. Since capacitance acts almost like a closed path, these oscillations can be grounded through the capacitor. Resistance is frequency agnostic; when the right value is chosen, it acts as an energy attenuator for high-frequency oscillations.

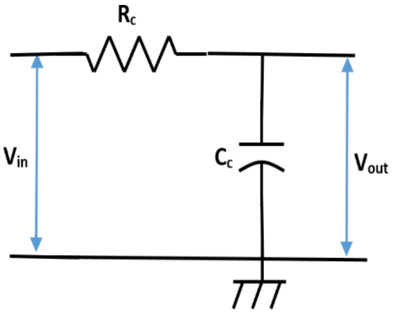


Fig 5 RC filter

The voltage gain of the RC filter is given as

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

And frequency response of RC filter can be defined as

$$f_c = \frac{1}{2\pi R_c C_c}$$

And time constant is given as

$$r = R_c C_c = \frac{1}{2\pi f c}$$

c. Ferrite Rings

VFTOs magnitude and gradient can be minimized by using ferrite rings around contacts of disconnector switches. This process is feasible, efficient, fast and commercially worthwhile. Attaching ferrite rings to the GIS bus bar is not much complex, and no need take any extra care in terns insulation levels. Depending on the possible peak value of transients and their characteristics, ferrite rings size and properties can be chosen. With respect to frequency impedance characteristics of ferrite rings alter considerably. Because of the permeability coefficient and inductance of the ferrite rings, the impedance provided by ferromagnetic material against VFTOs varies with frequency.

Impedance ferrite rings on VFTOs is given as

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

$\boldsymbol{L_e}$ is equivalent inductance, $\boldsymbol{f}$ frequency of transients

$$\boldsymbol{Z_f = j2\pi f \mu_r L = j2\pi f L(\mu_s' - j\mu_s'') \\ = 2\pi f L \mu_s'' + 2\pi f L \mu_s'}$$

Where $\boldsymbol{L}$ is inductance of the ferrite ring amd can be expressed as

$$\boldsymbol{L = \frac{\mu_o d}{2\pi} L \frac{R}{r}}$$

Ferrite rings offer high impedance path for the high frequency oscillations and low impedance path for the base frequency fundamental signals. Frequency response characteristics, loss and saturation characteristics, magnetic conductivity of the material used influence the ferrite ring parameters to be used. Figure 6 depicts the equivalent circuit of a parallel ferrite loop.

An appropriate equivalent inductance $\boldsymbol{Lf}$ is needed to obstruct the travelling wave circulation. The magnetic conductivity of the ferrite material, as well as the geometry of the ferrite rings and the busbar, will affect the value of this inductance. Resistance will absorb energy from travelling waves or voltage transients if the right value is chosen. There is a probability of high consumption of travelling waves energy and significant damping of voltage transients if the inductance and resistance values are well balanced.

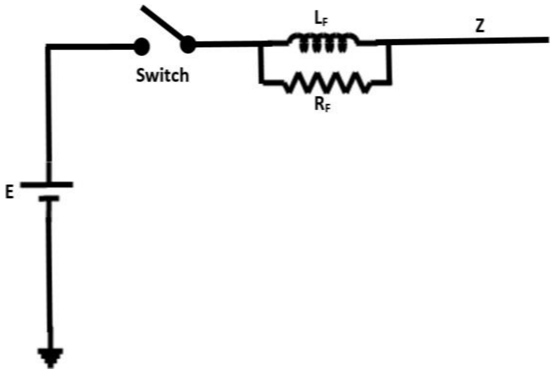


Fig 6. Equivalent circuit of Ferrite Rings

d. Nanocrystalline based Mitigation of VFTO

By wrapping Nanocrystalline rings around the GIS's inner conductor, fast voltage transients can be effectively mitigated. Nanocrystalline materials show improved rigidity, higher coercivity, better flexibility, less density, easily extensible, good electrical resistivity, higher thermal expansion coefficient, lower thermal conductivity, and greater soft magnetic properties in comparison to traditional coarse-grained materials. Silicon, iron and boron are the most commonly used metals used in nanocrystalline alloys. This material saturates when placed in a magnetic field. Because of current in inner conductors magnetic field strength of GIS is much higher than saturation field strength of nanocrystalline material. Hence, during low frequency range, there is no energy loss as nanocrystalline rings are magnetically saturated. For higher frequencies, energy loss occur, which means high frequency VFTOs can be mitigated due to this energy loss.

Due to the magnetization process of magnetic domains, the sloping anisotropy performance of nanocrystalline rings formed micro eddy currents. The losses produced by these micro eddy currents would help to conquer VFTOs. Figure 7 represents a nanocrystalline analogous circuit. By simulating the selected GIS substations with a variety of values, the resistance, inductance, and capacitance Rd, Ld, and Cd can be optimized, and the values that provide the best voltage transient mitigation can be chosen.

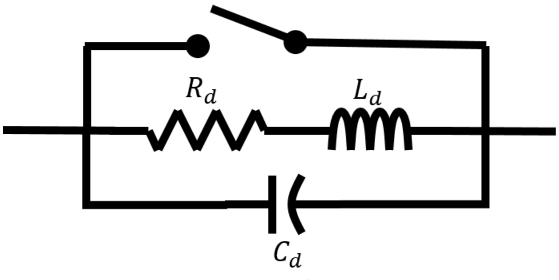


Fig 7. Equivalent Circuit of nanocrystalline ring

4. Simulation Results

Simulation using MATLAB/SIMULINK is performed on 765KV substation shown in figure 1 to check performance of four mitigation techniques to mitigate very fast transient overvoltages. Substation design for 765KV presented in [15] 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 mitigation techniques.

a. **Mitigation of VFTOs in 765KV GIS by Resistance**

A resistance of 635ohms is connected at each disconnector switch as a mitigating device. Switching operation is performed on disconnector switch CB1, due to which high frequency transient over voltages are generated. CB1 is switched off and contacts are opened to detach a part of the substation which contains the distribution transformer and consumer loads. Figure 8 presents VFTOs at B1 to B6 of substation without connecting any mitigating resistance. Figure 9 shows the VFTOs at various points (B1-B6) of substation due to switching operation of CB1 disconnector switch with resistor as mitigating device.

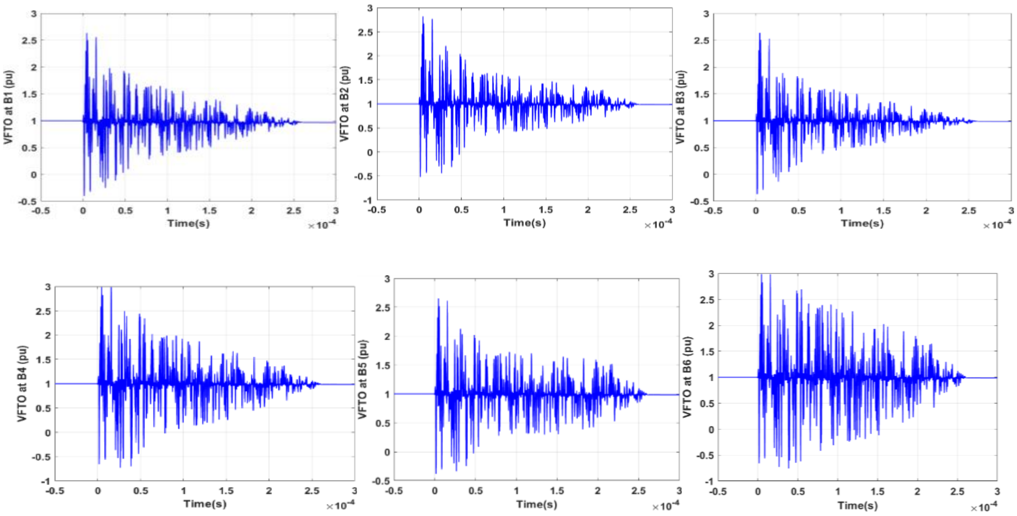


Fig **8. VFTOs at various points (B1-B6) of substation due to switching operation of CB1 disconnector switch without resistor as mitigating device**

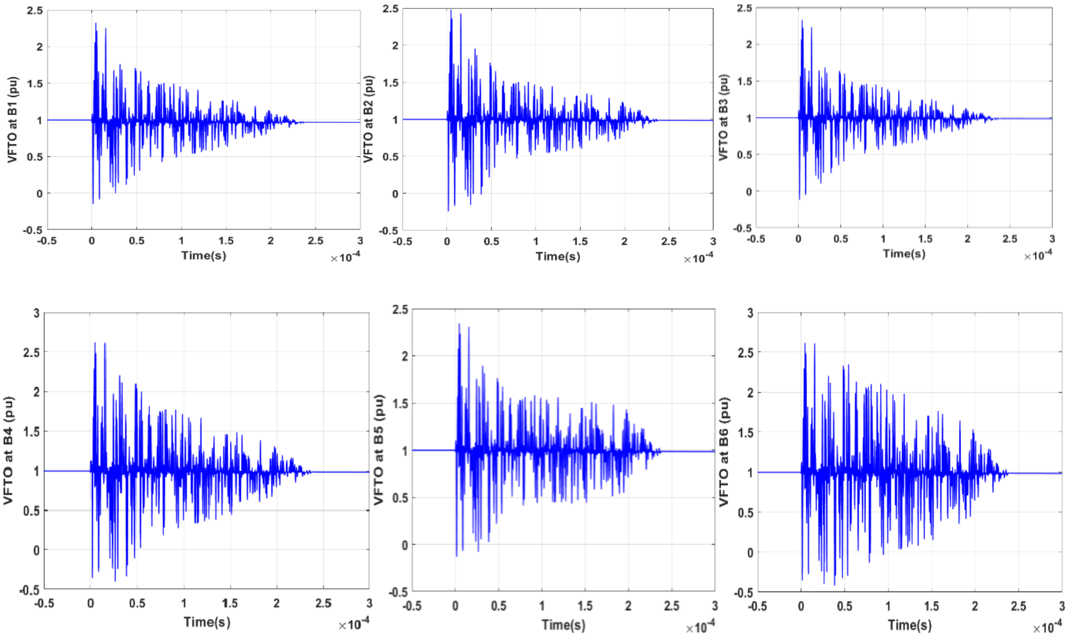


Fig 9. VFTOs at various points (B1-B6) of substation due to switching operation of CB1 disconnector switch with a resistor as mitigating device

The magnitude of transients, rise time, and settling time at different substation locations as a result of disconnector switch CB1 switching are shown in the table. Addition of resistance in series with disconnector switch reduces peak value pf voltage transients by 10% and settling time is also reduced by 20-30 µseconds. The consequence of transients on other positions is determined by the load current portion at that specific location. The optimal resistance value is determined by simulating the device for various resistance values.

Figure 10 shows VFTOs at the B1 and B2 locations of the substation for four different resistance values. As compared to other resistances, voltage transient magnitudes and settling times are lower for resistance 635ohms.

TABLE 4.1. VFTOS MAGNITUDE, SETTLING TIME AND RISE TIME FOR 765KV SUBSTATION WITHOUT AND WITH MITIGATING DEVICE

Measured Location	Without additional resistance			With additional resistance as mitigating device		
	Magnitude (p.u.)	Rise time (µ sec)	Settling time (µ sec)	Magnitude (p.u.)	Rise time (µ sec)	Settling time (µ sec)
CB1	2.61	1.52	263.3	2.38	1.36	242.5
CB2	2.79	1.48	258.9	2.41	1.24	238.36
CB3	2.63	1.69	261.23	2.21	1.33	243.85
CB4	3.01	1.86	260.5	2.5	1.52	241.85
CB5	2.6	1.78	258.35	2.31	1.41	232.6
CB6	3.01	1.72	250.32	2.5	1.34	230.51

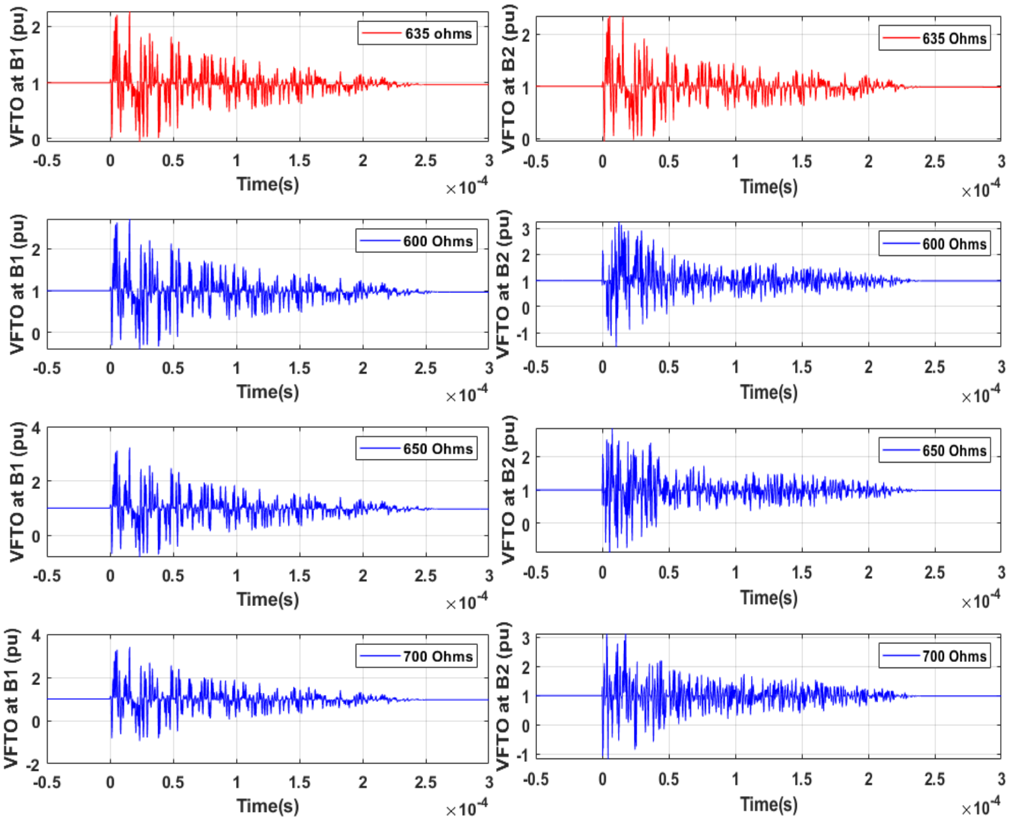


Fig 10. VFTOs at B1 and B2 locations of substation for 4 different values of Resistance

b. Suppression of VFTOs in 765 KV GIS by RC Filter

An RC filter is connected with disconnector switch to mitigate the VFTOs generated with switching operation. Resistance and capacitance values of mitigating device are optimized by simulating the VFTOs for various conditions. After connecting RC filter with disconnector switch generated VFTOs are presented in figure 11. After instantaneous opening of the switch CB1, generated high frequency oscillations are presented in figure 11. Optimized values of resistance and capacitance are 348ohms and 0.29F. Due to effective redirection of high frequency oscillations, the peak value of voltage transient after adding RC filter is around 2p.u.

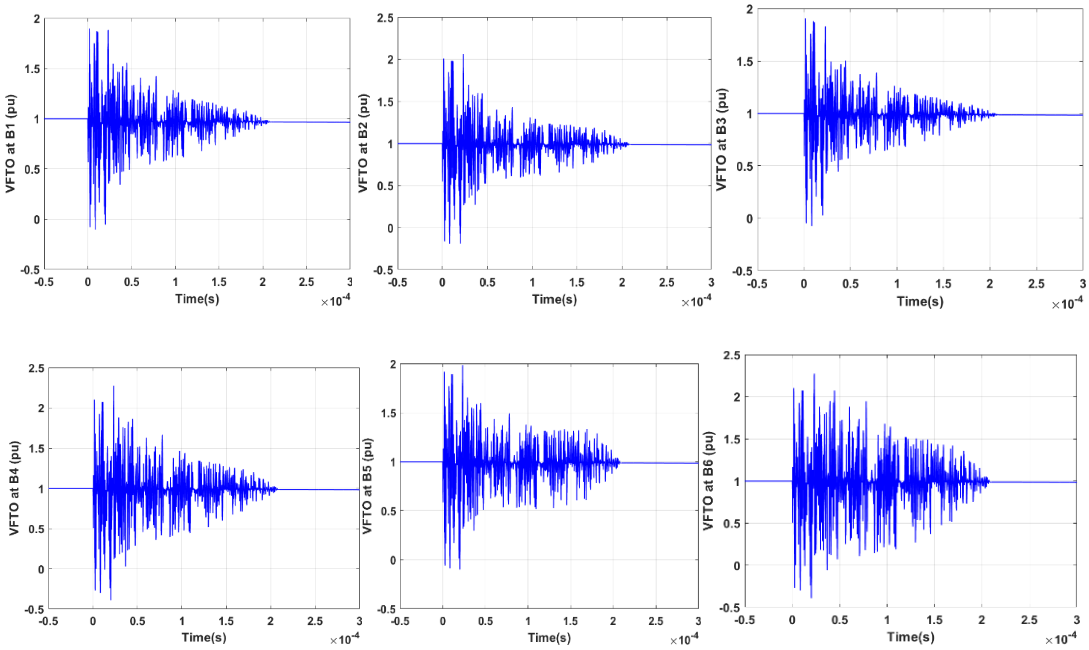


Fig 11. VFTOs at various points (B1-B6) of substation due to switching operation of CB1 disconnector switch with RC Filter as mitigating device

Table 5.1 shows the magnitude of transients, rise period, and settling time at different substation locations due to the switching of the disconnector switch (CB1) for resistor and RC filter as a mitigating system. The voltage transient magnitudes are reduced by 22% and the settling time is reduced by 30-40 seconds after replacing resistance with an RC filter as a mitigating device in the disconnector switch.

The VFTOs shown at other locations will be affected by the load current. As a result, the peak magnitude of VFTOs varies between 2.2-2.5 p.u. when using resistance and 1.8-2.2 p.u. when using an RC filter. Figure 12 shows the VFTOs at the B1 and B2 positions of the substation for four different RC filter values.

Table 5.1. VFTOs magnitude, settling time and rise time for 765KV substation with resistor and RC filter as mitigating device

Measured location	With additional resistance as mitigating device			With RC filter as mitigating device		
	Magnitude (p.u.)	Rise time (μ sec)	Settling time (μ sec)	Magnitude (p.u.)	Rise time (μ sec)	Settling time (μ sec)
CB1	2.38	1.36	242.5	1.85	1.19	203.25
CB2	2.41	1.24	238.36	2.02	1.18	210.3
CB3	2.21	1.33	243.85	1.92	1.185	205.36

CB4	2.5	1.52	241.85	2.2	1.23	210.3
CB5	2.31	1.41	232.6	2.0	1.19	208.9
CB6	2.5	1.34	230.51	2.21	1.169	207.65

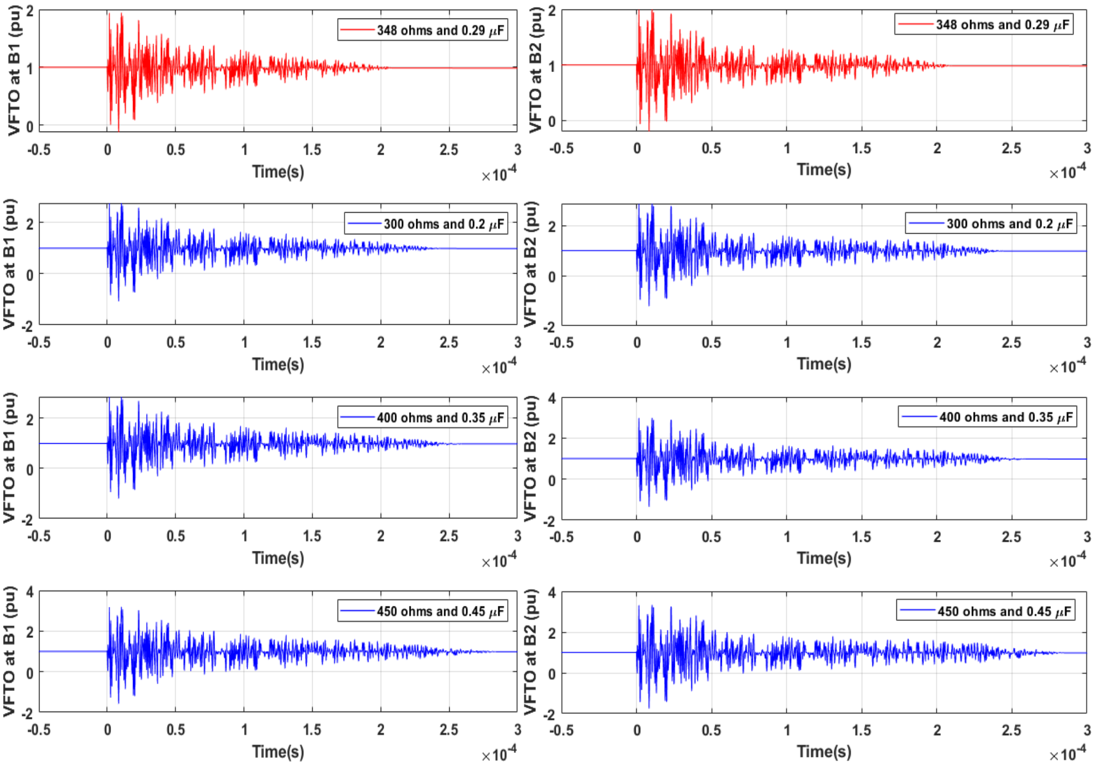
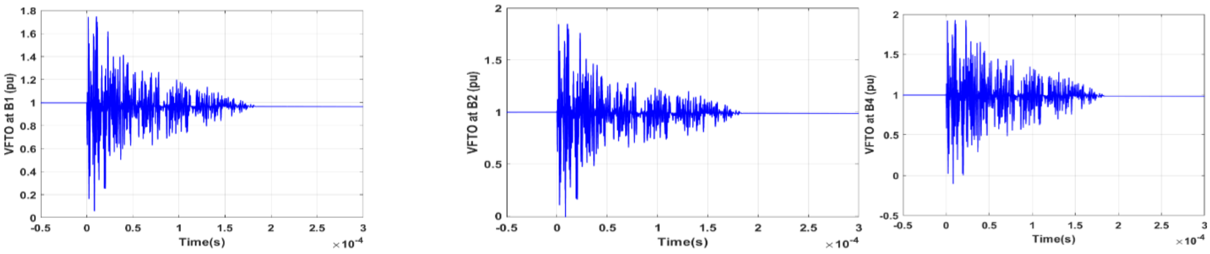


Fig 12. VFTOs at B1 and B2 locations of substation for 4 different values of resistance and capacitor in RC filter

c. Suppression of VFTOs in 765 KV GIS by Ferrite Rings

An Ferrite ring is connected with disconnector switch to mitigate the VFTOs generated with switching operation. Resistance and inductance values of mitigating device are optimized by simulating the VFTOs for various conditions. After connecting tis device with disconnector switch generated VFTOs are presented in figure 13. After instantaneous opening of the switch CB1, generated high frequency oscillations are presented in figure 13. Optimized values of resistance and inductance are 225ohms and 2mH. Due to successful reduction of high frequency oscillations, the peak value of voltage transient after inserting ferrite ring is in and about 2p.u., and this peak value is reduced to 1.6p.u. after replacing RC filter with Ferrite rings.



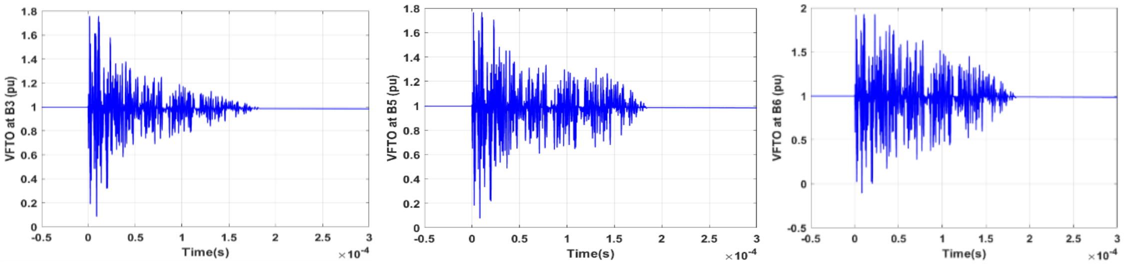


Fig 13. VFTOs at various points (B1-B6) of substation due to switching operation of CB1 disconnector switch with Ferrite rings as mitigating device

VFTOs with Ferrite rings are shown in Figure 13 at locations B1-B6. Table 6.1 shows the magnitude of transients, rise period, and settling time at different substation locations due to the switching of the disconnector switch (CB1) for the RC filter and Ferrite rings as a mitigating system. Figure 14 shows the VFTOs at the B1 and B2 positions of the substation for four separate Ferrite ring values.

Table 6.1. VFTOs magnitude, settling time and rise time for 765KV substation with RC Filter and Ferrite Ring as mitigating device

Measured location	With RC Filters mitigating device			With Ferrite ring as mitigating device		
	Magnitude (p.u.)	Rise time (µ sec)	Settling time (µ sec)	Magnitude (p.u.)	Rise time (µ sec)	Settling time (µ sec)
CB1	1.85	1.19	203.25	1.69	1.15	162.5
CB2	2.02	1.18	210.3	1.68	1.141	163.85
CB3	1.92	1.185	205.36	1.71	1.142	169.21
CB4	2.2	1.23	210.3	1.82	1.175	162.85
CB5	2.0	1.19	208.9	1.78	1.149	160.78
CB6	2.21	1.169	207.65	1.83	1.115	160.5

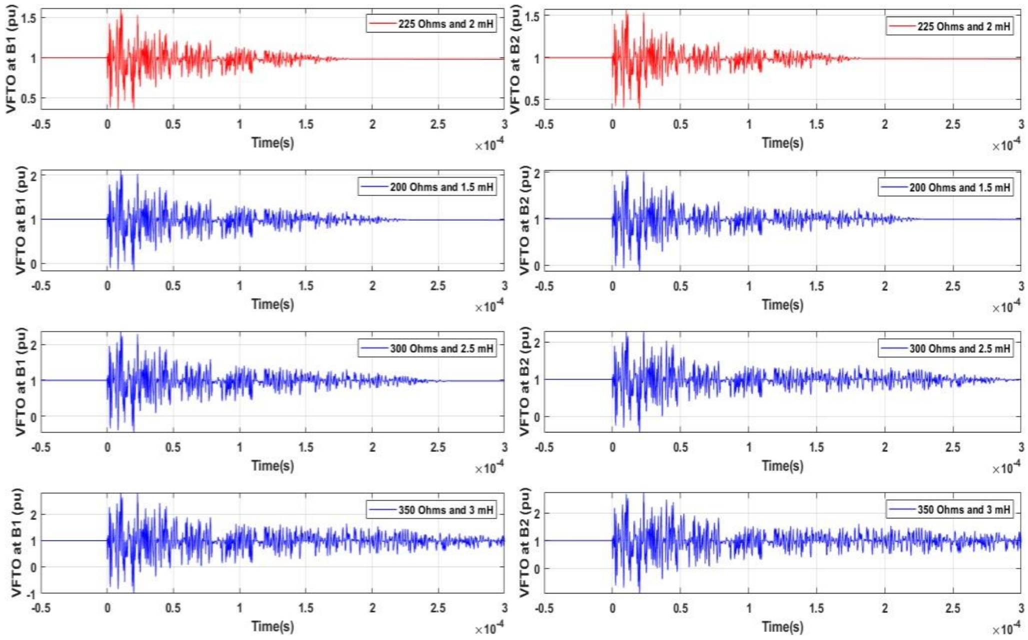


Fig 14. VFTOs at B1 and B2 locations of substation for four different values of resistor and inductor in Ferrite Rings

d. Mitigation of VFTOs in 765 KV GIS by Nanocrystalline Rings

Disconnect switch CB1 is suddenly opened, and the results of VFTOs at different substation points are shown. Figure 7 demonstrates an analogous circuit of a nanocrystalline ring, with resistance, inductance, and capacitance of 135ohms, 0.82mH, and 2.56 F, respectively. By comparing the damping effect of VFTOs by nanocrystalline rings with different values, these values are optimized. Due to efficient dissipation of energy by eddy currents and hysteresis currents, the peak value of voltage transient using ferrite ring as mitigating system is in and about 1.6p.u., and this peak value is reduced to 1.1p.u. after replacing ferrite ring with nanocrystalline rings.

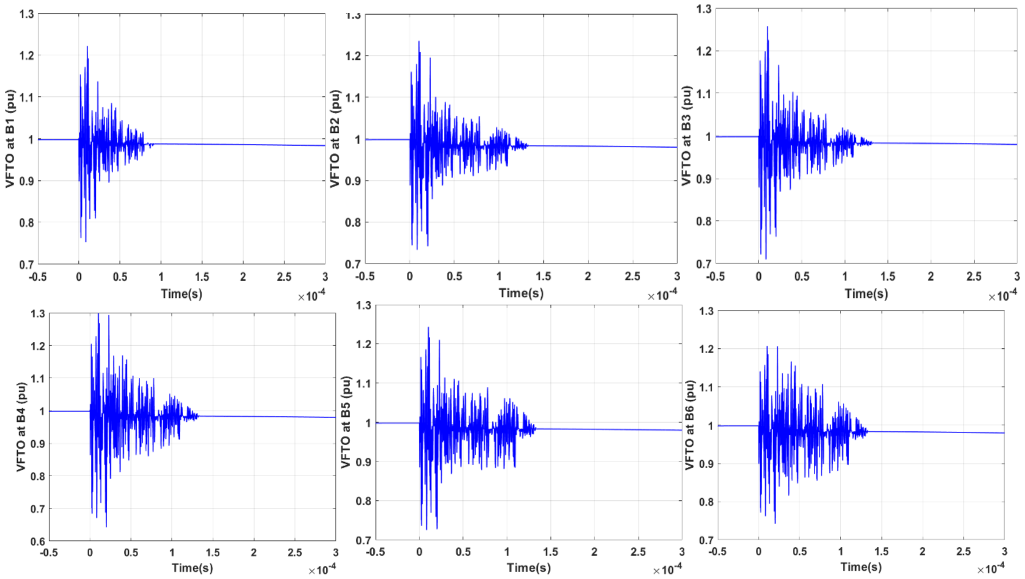


Fig 15. VFTOs at various points (B1-B6) of substation due to switching operation of CB1 disconnector switch with Nanocrystalline as mitigating device

Figure 15 depicts the effect of VFTOs at B1-B2 positions for four different values of nanocrystalline rings. Table 7.1 shows the magnitude of transients, rise period, and settling time at different substation locations caused by the switching of the disconnector switch (CB1) for ferrite rings and nanocrystalline rings as mitigating devices. By replacing the ferrite rings with nanocrystalline rings , the peak value of voltage transients is reduced by 30% and the settling time is reduced by 40- 50 seconds.

Table 7.1. VFTOs magnitude, settling time and rise time for 765KV substation with ferrite ring and nanocrystalline as mitigating device

Measured location	With Ferrite Rings as mitigating device			With Nanocrystalline as mitigating device		
	Magnitude (p.u.)	Rise time (µ sec)	Settling time (µ sec)	Magnitude (p.u.)	Rise time (µ sec)	Settling time (µ sec)
CB1	1.69	1.15	162.5	1.22	0.982	83.3
CB2	1.68	1.141	163.85	1.23	0.993	121.32
CB3	1.71	1.142	169.21	1.24	0.992	120.6
CB4	1.82	1.175	162.85	1.29	1.015	119.85
CB5	1.78	1.149	160.78	1.22	0.998	121.7
CB6	1.83	1.115	160.5	1.2	0.993	120.85

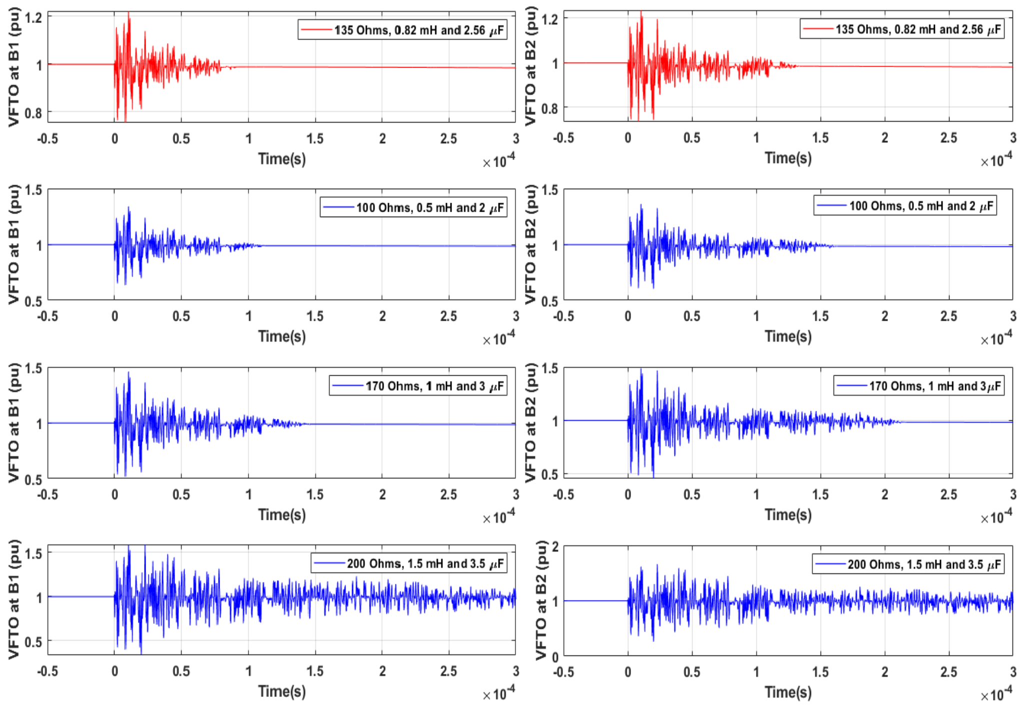


Fig 16. VFTOs at B1 and B2 locations of substation for 4 different values of resistor, inductor and capacitor in Nanocrystalline

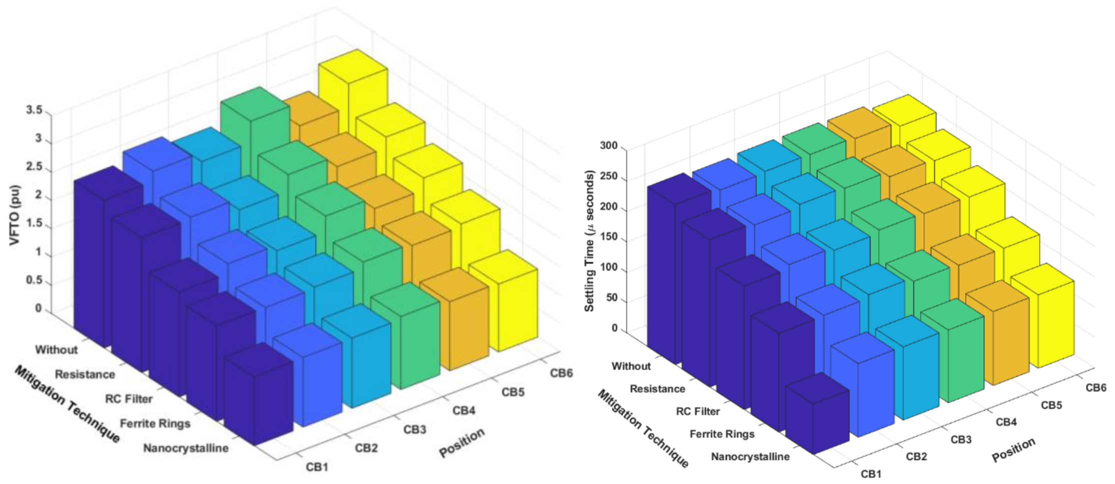


Fig 17 . Peak value of VFTO and settling time comparison at different positions of substation for different mitigation techniques.

Comparison between adopted four mitigation techniques in terms of VFTOs peak value and settling time are presented in figure 17. Proposed Nanocrystalline rings are efficient in mitigating the VFTOs compared to remining three techniques.

5. Conclusion

VFTOs are major factor to be considered in extra high voltage GIS substations, in which the ratio between impulse withstand voltage and fundamental rated voltage is small. Mitigating techniques are need to be adopted to reduce effect of VFTOs on other equipment of substation. Four techniques are presented to suppress VFTOs in a 765KV EHV substation and results are compared in terms of peak value, rise time and settling time of oscillations. Optimization of parameter values of these techniques is done by performing number of simulations on 765KV substation. Components of the substation are modelled based on their behavior for high frequency oscillations. From the simulation results and comparison, it can be concluded that performance of nanocrystalline rings as mitigating devices is efficient compared to other three techniques.

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