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Suppression of Very Fast Transient over Voltages in Gas Insulated Substations using RC Filters

R.Durga Rao
Asst. Professor &Head Dept of EEE, JNTUHCEM,Hyderabad, India
e-mail: durgarao@jntuh.ac.in
Dr.M.Surya Kalavathi
Professor(on-lien) Dept of EEE, JNTUH Vice-Chancellor, Yogi Vemana University, Kadapa, India
e-mail: munagala12@jntuh.ac.in

Abstract:-this paper presents RC Filter based mitigation technique of Very fast Transient Over Voltages(VFTOs) in Gas Insulated Switch gear based substations. Gas Insulated Substations (GIS) are broadly used for transmission and distribution of electric power. In Gas Insulated Substations (GIS), through the switching events of disconnector switches a numeral restrikes will arise and this leads to generation of Very Fast Transient Over voltages (VFTO). Due to frequent occurrences of VFTOs, the life of the insulation in the system will be reduced. It may lead to flashover. In this work to reduce these VFTOs, disconnector switches are rearranged by adding additional RC Filters as mitigating devices. Four Substations with different voltage ratings (765KV, 1000KV, 1200KV and 1500KV) are chosen to check effectiveness of RC filter as mitigating device in reducing VFTOs. Substation is modelled and results are presented in MATLAB/SIMULINK.
Keywords- Gas Insulated Switch Gear, SF6 circuit breaker, RC Filters, VFTO, sim power system

I. Introduction

By relying on the outstanding electrical insulation behavior of Sulphurhexafluoride(SF6), Gas insulation technology was developed. SF6 is an artificial gas which is non-toxic, non-flammable, non-corrosive, inert and is stable over the long term [1]. SF6based insulation technology was developed in the 1920s, and because of its exceptional electrical properties allowed high voltage and high current rating systems to be considered. The first closed chamber for an experimental set-up was built in 1960 using SF6 under high voltage conditions for both DC and AC voltages[2]. Switching efficiency of circuit breakers will be increased due to SF6 gas unresolved arc interruption performance. And hence it leads to the development of high voltage switchgear with an enormously high switching ability and consistency [3].

In Gas Insulated Substations (GIS), through the switching contacts a numeral restrikes will arise after disconnector switch or circuit breaker is functioned and this leads to generation of Very Fast Transient Over voltages (VFTO). Rise time of these generated VFTO is in the range of few nano seconds and due to this high frequency oscillations will occur[4]. Frequency range of

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VFTOs is from 100Khz to hundreds of MHz.Inaddition, with opening or closing of disconnector switch, VFTOs are due to also other actions such as process of a circuit breakers operation or grounding switches. An electromagnetic wave is produced due to switching operation, which circulates along the busbars and substation components. In substation equipment it may reflect multiple times at joints and its maximum overvoltage peak values can reach significant levels. Magnitude of these VFTOs will be in range of 1.5 to 2.0 p.u. and they may reach as high as 2.5 p.u. to 3 p.u. in case of ultra-high voltage systems. Comparing with basic insulation levels these values are less than these levels but due to frequent occurrences aging and degradation process of insulations may speed up.

Due to frequent occurrences of VFTOs, the life of the insulation in the system will be reduced. It may lead to flashover if the dielectric strength of SFs in the presence of free metallic particles is reducedbecause of VFTOS. Components of gas insulated substations such as transformers in which interturn insulation may be stressed due to higher voltage than under chopped lighting impulse voltage also effected due to VFTOs high magnitude and high frequency oscillations.

In [5], transient behavior of GIS is evaluated numerically and experimentally using electrical equivalent circuits of GIS components and the generation and propagation of transients inside GIS also evaluated. In [6], different GIS component models are developed and experiments are conducted with regard to waveform distortion on various models consisting of spacers, bushing etc. suppression method of transient over voltages caused by dis-connector switch using insertion of resistor with appropriate value during switching operation was explained in[7]. Using various formulae high current pulsed arc resistance was determined in [8] and it indicated that initial stages of discharge will be in less than o.5 µseconds. Using metal oxide arrester and resistance switching suppression very fast transient over voltages in GIS systems was explained in [9] and results are compared with measured results. The results show that VFTO'S are suppressed up to some extent.

In this paper, a suppression technique for VFTOs using RC filter is proposed for four different ultra-high voltage rated substations. to suppress the over-voltage transients RC filter can be inserted discharge path at which electrodes are with long gap and discharge voltage is high. To optimize parameters of RC filter for efficient suppression of VFTOs, GIS is modelled by making capacitance as dominating parameter due to presence of high frequency oscillations in VFTOs.Four ultra-high voltage substations are modelled in MATLAB/SIMULINK using each component equivalent circuits. Section II explain about modelling of VFTOs in GIS substation, section III about mitigation technique proposed and section IV presents results and discussion.

II. Modelling of VFTOs

Capacitance is dominating parameter to model behavior of VFTOs as dominated high frequency oscillations presented in it. Frequency range is from tens of KHz to some hundreds of MHz. at

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these high frequencies GIS bus acts like a transmissionline with a finite transit time and propagation velocity as length of GIS bus is smaller than ordinary substationthe value of surge impedance of GIS busbar which is modelled as transmission line is given as

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

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

Surge impedance the value which dominates speed and elemental length of wave propagation and phase to ground capacitances should be chosen appropriately due to travelling nature of over voltage transients. A lumped capacitance can be used to represent spacers and elbows.Whilemodelling UHV rated power transformer, its behavior for high frequency oscillations should be considered. HV bushings can be represented using inductance, resistance and capacitance.

Disconnector switches can be modelled differently for closing and opening operation. Closing operation of disconnector switch can be modelled as an exponentially decreasing resistance from high value to zero and is given as

$$R_{spark} = R_0 e^{-t/\tau}$$

R_{spark} is spark resistance, R_0 is equal to $10^8\Omega$, t is formative time, τ is time constant in range of 0.5 nano seconds.

Circuit breakers in opening state ismodelled as two transmission lines in series with a capacitance and series resistance in between them. Closed state of circuit breaker can be modelled by replacing capacitance with surge impedance. Overhead line in GIS is considered as a transmission line ended with a resistance equal to surge impedance.

III. Suppression of VFTOs by RC filter

For protecting load from high frequency components RC filters can be used widely. Over voltages due to arcing in vacuum circuit breakers also suppressed by RC filters [10]. Attenuation of energy due to high frequency components is done by resistance R and high frequency oscillations can be filtered capacitance C. RC filter with disconnector switch suppress very high voltage transients by redirecting high frequency oscillations in it.

Magnitude of resistance and capacitance in RC filter depends on frequency and magnitude of voltage transients.Typical structure of RC filter design is shown in fig 1. Reactance offered to high frequency oscillations by capacitance is inversely proportional to frequency of oscillations. Hence for high frequency oscillations capacitance almost behaves like a closed path due to which these oscillations can be grounded through the capacitor. Resistance is independent of frequency, by properly choosing its value it behaves like an energy attenuation for high frequency oscillations.

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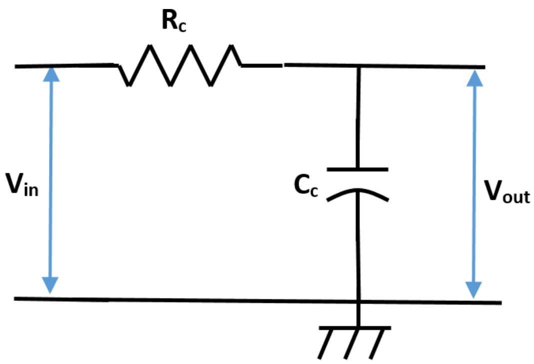

Fig 1. RC filter

Voltage gain of RC filter is given as

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

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

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

R and C parameters of filter can be optimized using effective voltage gain and cut off frequency for four UHV rated substations.Basic structure and single line diagrams of four substations and their constant parameters are taken from literature [11].

A. 765 KV Substation

Single line diagram of 765 KV substation is shown in fig 2 [12]. Normal source and back up source are connected to substation due to local requirements. 6 Disconnector switches at positions CB1-CB6 are switched to analyze VFTOs. By connecting RC filter to these disconnector switches voltage transients are suppressed. Optimization of R and C values is achieved by considering magnitude and frequencies to be attenuated using equations mentioned in above section.

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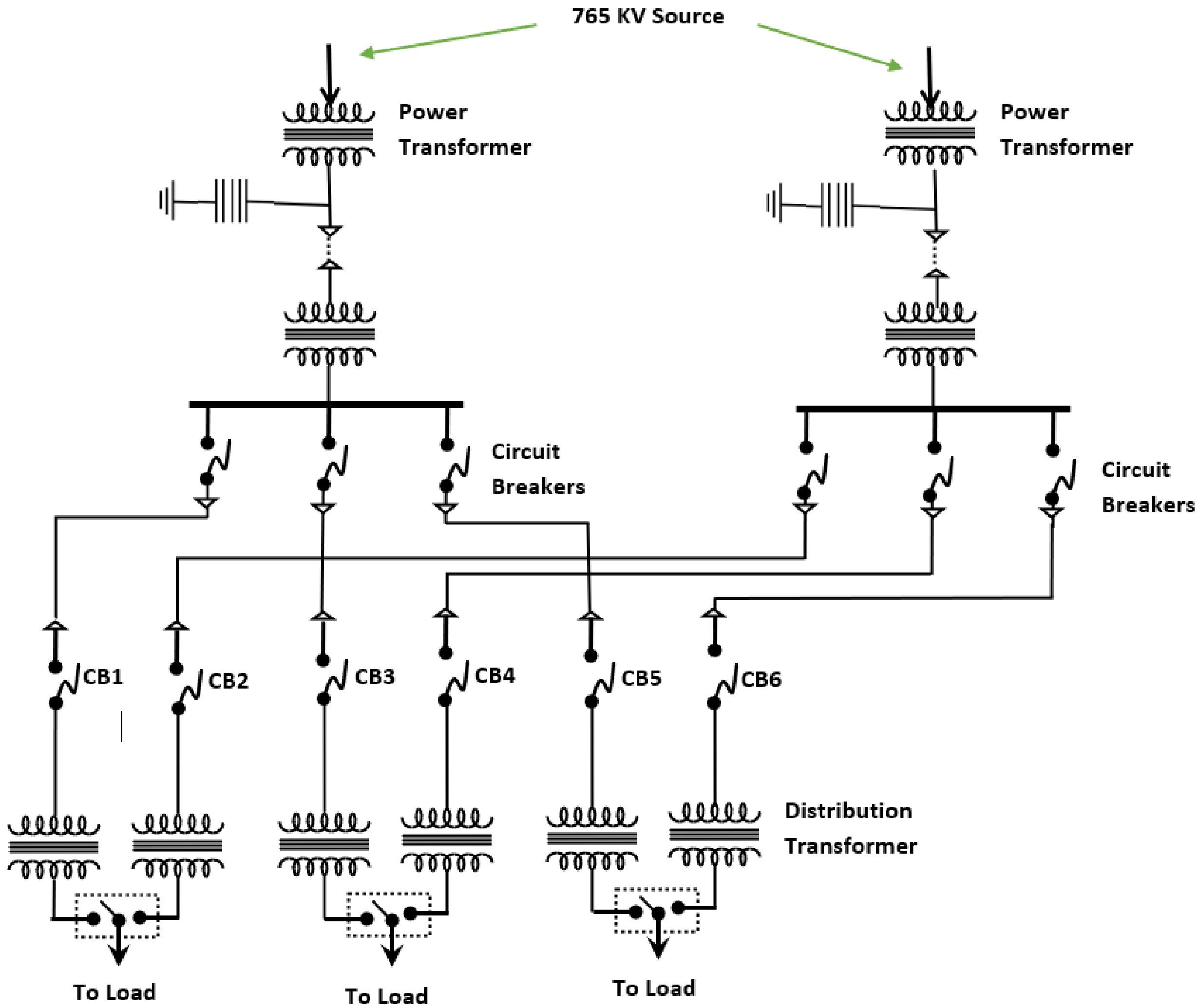

Fig 2. Single line diagram of 765KV substation

B. 1000 KV substation

Single line diagram of Huainnan-Wannan 1000 KV UHV transmission system is shown in fig 3 [13]. Transmission line with UHV of 1000 KV is a double circuit transmission line on same tower. Substations are located at Huainnan and wannan locations and both are based on GIS switchgear. Single line schematic diagram of Huainnan substation is shown in fig 3 [13]. CB1-CB6 aredisconnector switches which are operated to study effect of VFTOs on system and their process of suppression by adding RC fiters. PT1-PT2 are voltage transformers and T1-T2 are auto transformers. Length of busbars are mentioned in single line diagram.

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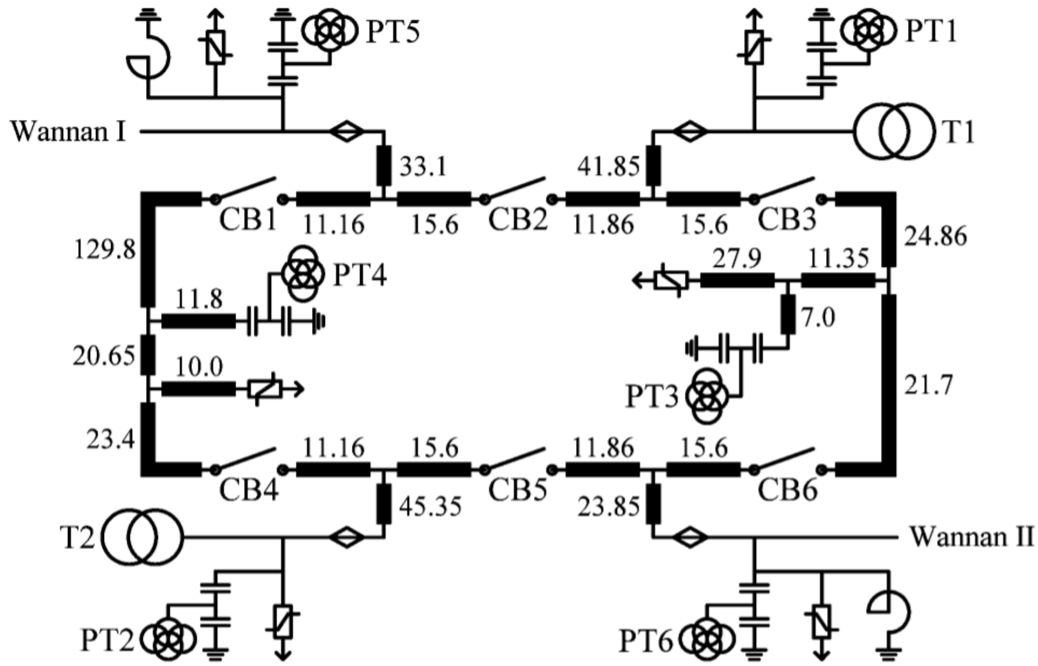

Fig 3. Single line diagram of 1000KV substation

C. 1200 KV and 1500 KV Substation

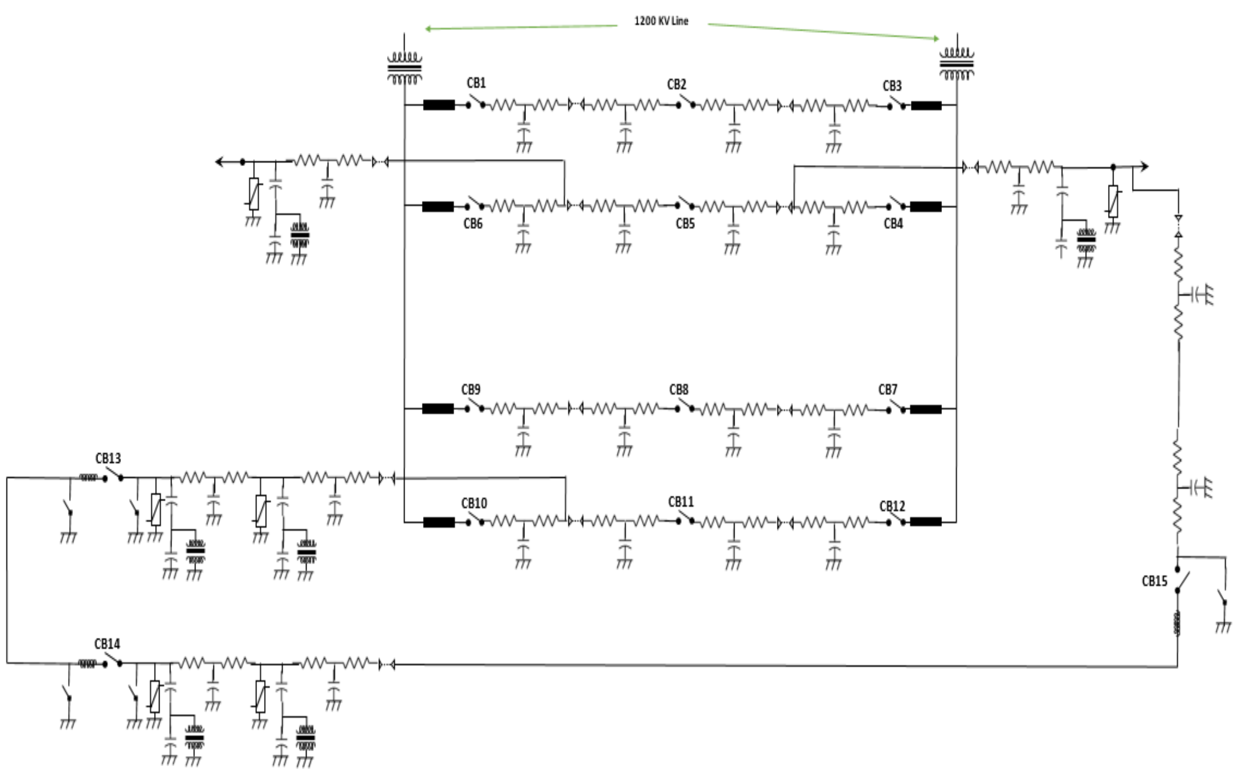

Fig 4. Single line diagram of 1200KV substation

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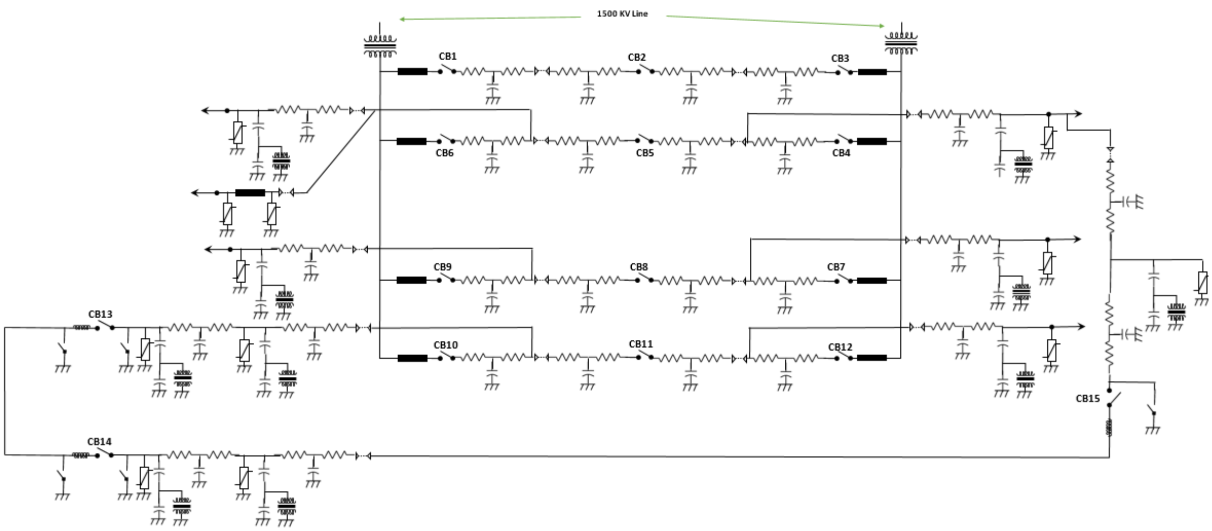

Fig 5. Single line diagram of 1500KV substation

A 1200 KV test station at Bina, Madhya Pradesh India is chosen to study effect of VFTOs. This test station is modified by adding additional protecting devices like MOVs. Single line diagram of test system for 1200 KV is shown in fig 4 and for 1500 KV with additional protecting devices is shown in fig 5 [14]. Important factor to be considered for UHV substation is coordination insulation levels of various equipment in point of withstanding capability of lighting impulse and switching impulse voltage. CB1-CB15 are the disconnector switches which are operated to study VFTOs and their suppression using mitigating device.

IV. Simulation Results

Four ultra-high voltage rated substations (765 KV, 1000 KV, 1200 KV and 1500 KV) are modelled considering each components behavior to high frequency oscillations to analyze VFTOs after and before connecting suppression device. Single line diagram of substations isshown in fig [5-8] transient over voltages due to switching events of disconnector switches are recorded with resistance and with RC filter as mitigating devices. Optimization of resistance values for same UHV substations is discussed by same author in his previous work [15]. Models developed using equivalent circuits of each apparatus by taking consideration of VFTOs give accurate results of transients and magnitudes of these transients, settling times and their rise time are assessed and tabulated.

a. Result analysis for 765 KV

Disconnector switch CB1 is opened at an instant and results of VFTOs at various points of substation are presented.A resistance of 635Ω is added to each disconnector switch as a mitigating device for VFTOs. Voltage transients after connecting resistor are presented in fig 6. An RC filter of 348 ohms of resistance and 0.29 µF of capacitance is connected to each disconnector switch and respective results after switching event of CB1 is presented in fig 7. The peak value of voltage transient after adding resistance is in and around 2.5p.u. and this peak value is decreased to 2p.u. after replacing resistor with RC Filter due to effective redirection of high frequencyoscillations.

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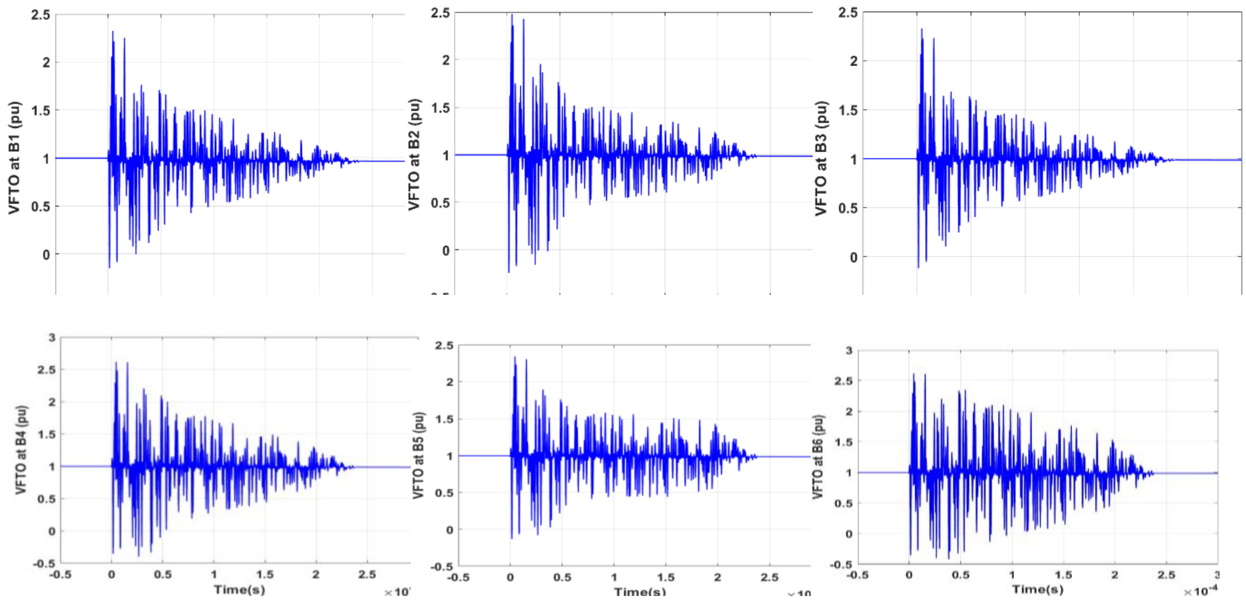

Fig 6. VFTOs at various points (B1-B6) of substation due to switching operation of CB1 disconnector switch with resistor as mitigating device

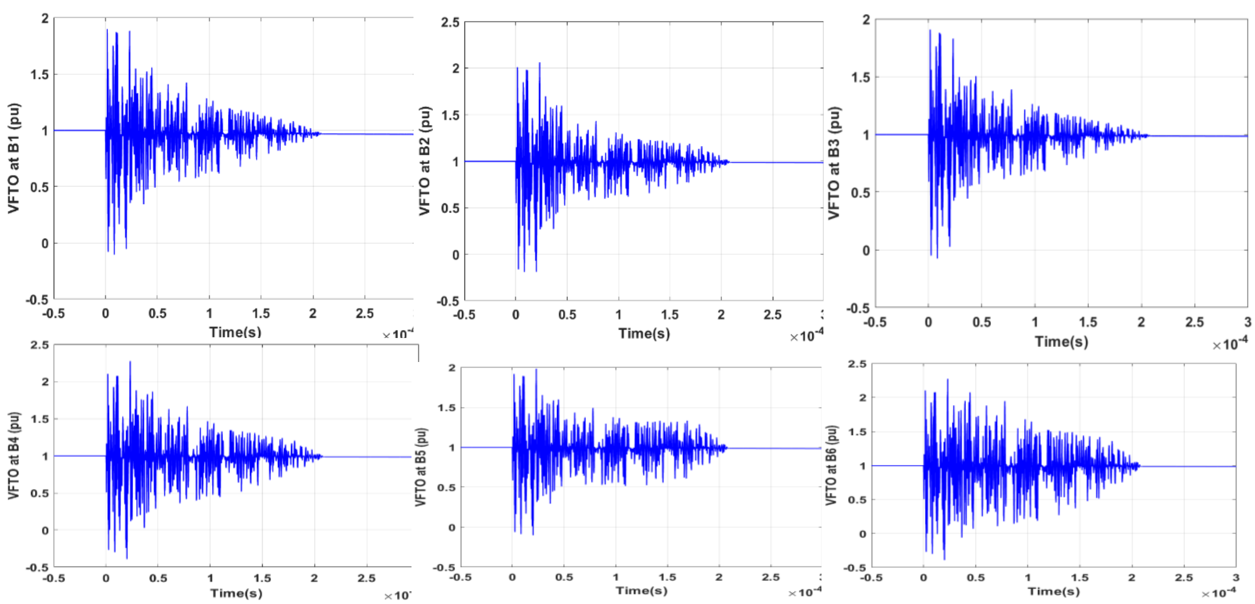

Fig 7. VFTOs at various points (B1-B6) of substation due to switching operation of CB1 disconnector switch with RC Filter as mitigating device

Fig 7 presents VFTOs at locations B1-B6 with RC filter. Magnitude of transients, rise time and settling time at various locations of substation due to switching of disconnector switch (CB1)for resistor and RC filter as mitigating device is shown in table 1. After replacing resistance with RC filter as mitigating device in disconnector switch reduces voltage transient magnitudes by 22%

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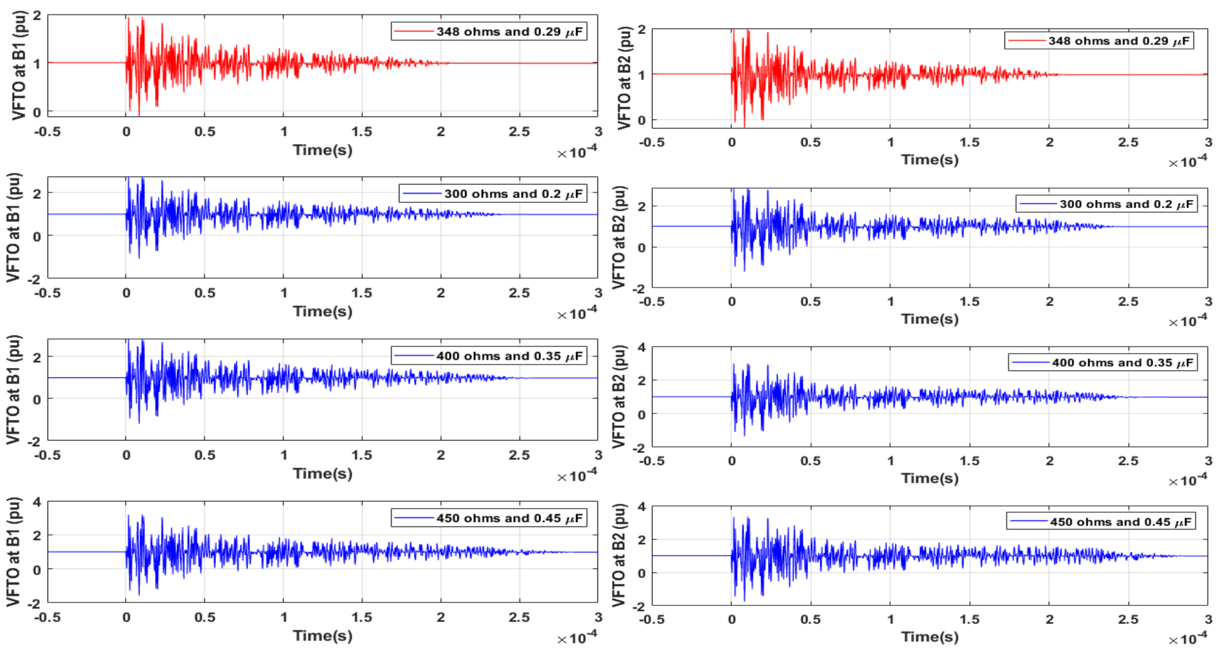
and reduces settling time by 30-40 μ seconds. Load current will influence the VFTOs presented at other locations. Hence peak magnitude of VFTOs is changing in between 2.2-2.5 p.u. with resistance and 1.8-2.2 p.u. with RC filter. VFTOs at B1 and B2 locations of substation for 4 different values of RC filter are shown in fig 8.

Table 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



(a) (b)

Fig 8. VFTOs at B1 and B2 locations of substation for 4 different values of resistance and capacitor in RC filter

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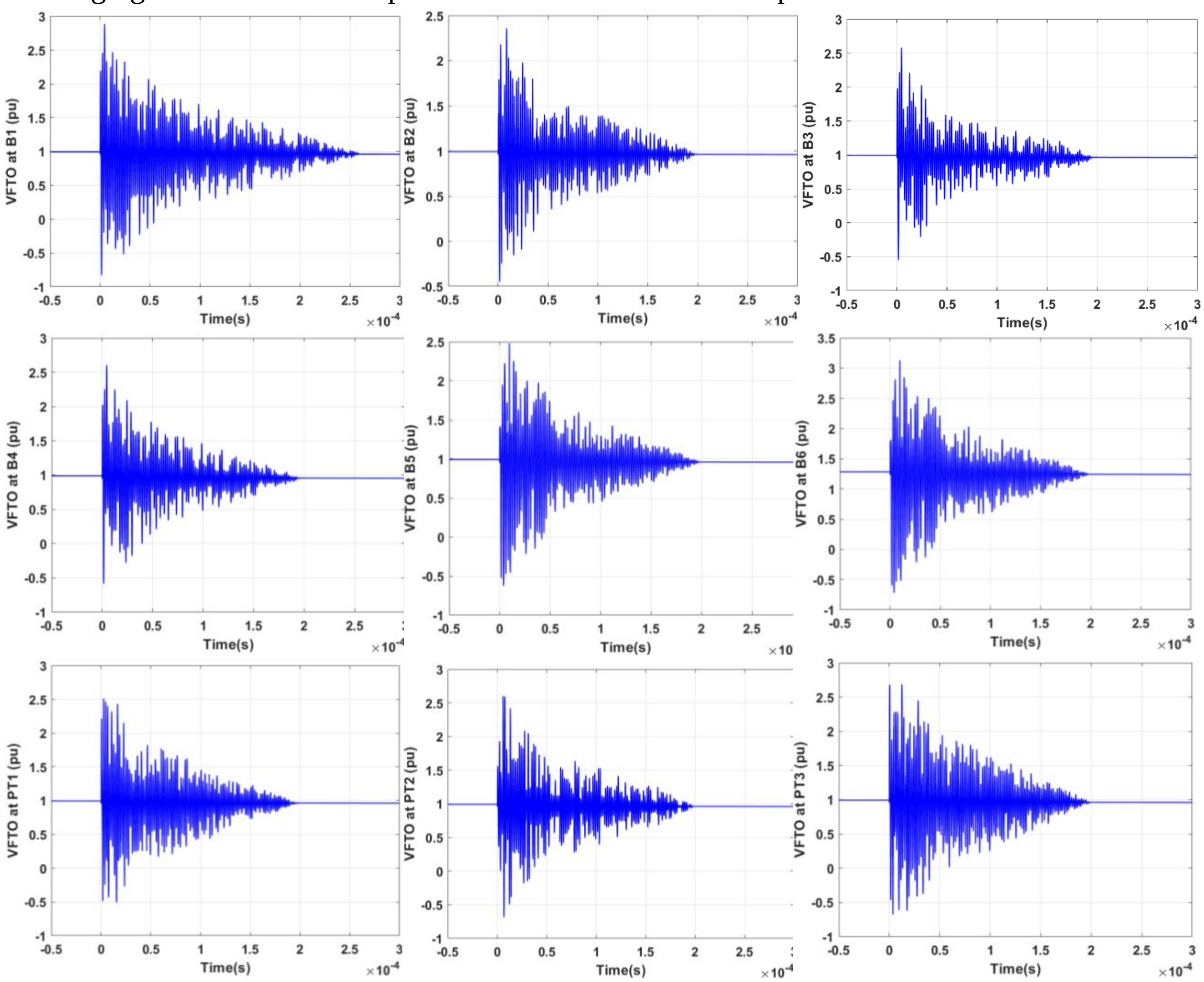
b. Result analysis for 1000 KV substation

Disconnector switch CB1 is operated by switching off to check fast voltage transients and these transient effects on other apparatus. Fig 9 shows voltage transients at various points of substation due switching event of CB1 after adding resistor as mitigating device. An RC filter of 258 ohms resistance and 0.85 µF capacitor is added to each disconnector switch and voltage transients are recorded and shown in fig 10. The peak value of voltage transient after adding resistance is in and around 2.5p.u. and this peak value is decreased to 1.8p.u. after replacing resistor with RC Filter due to effective redirection of high frequency oscillations. Effect of VFTO at B1 and B2 position for 4 different values of RC filter is shown in fig11. Magnitude of VFTOs, rise time and settling time before and after adding resistance and RC filter as mitigating devices is tabulated in table. After replacing resistance with RC filter as mitigating device in disconnector switch reduces voltage transient magnitudes by 34% and reduces settling time by 30-40 µ seconds. Load current will influence the VFTOs presented at other locations. Hence peak magnitude of VFTOs is changing in between 2.3-2.7 p.u. with resistance and 1.7-2.1 p.u. with RC filter.



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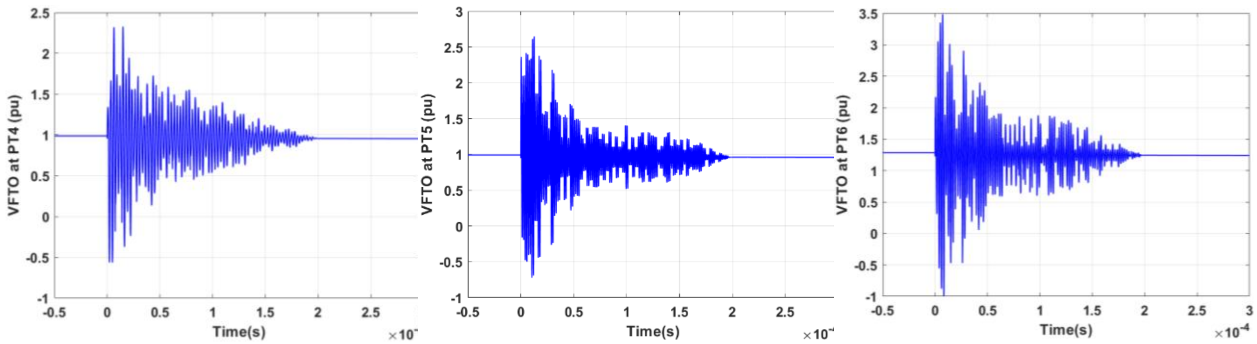
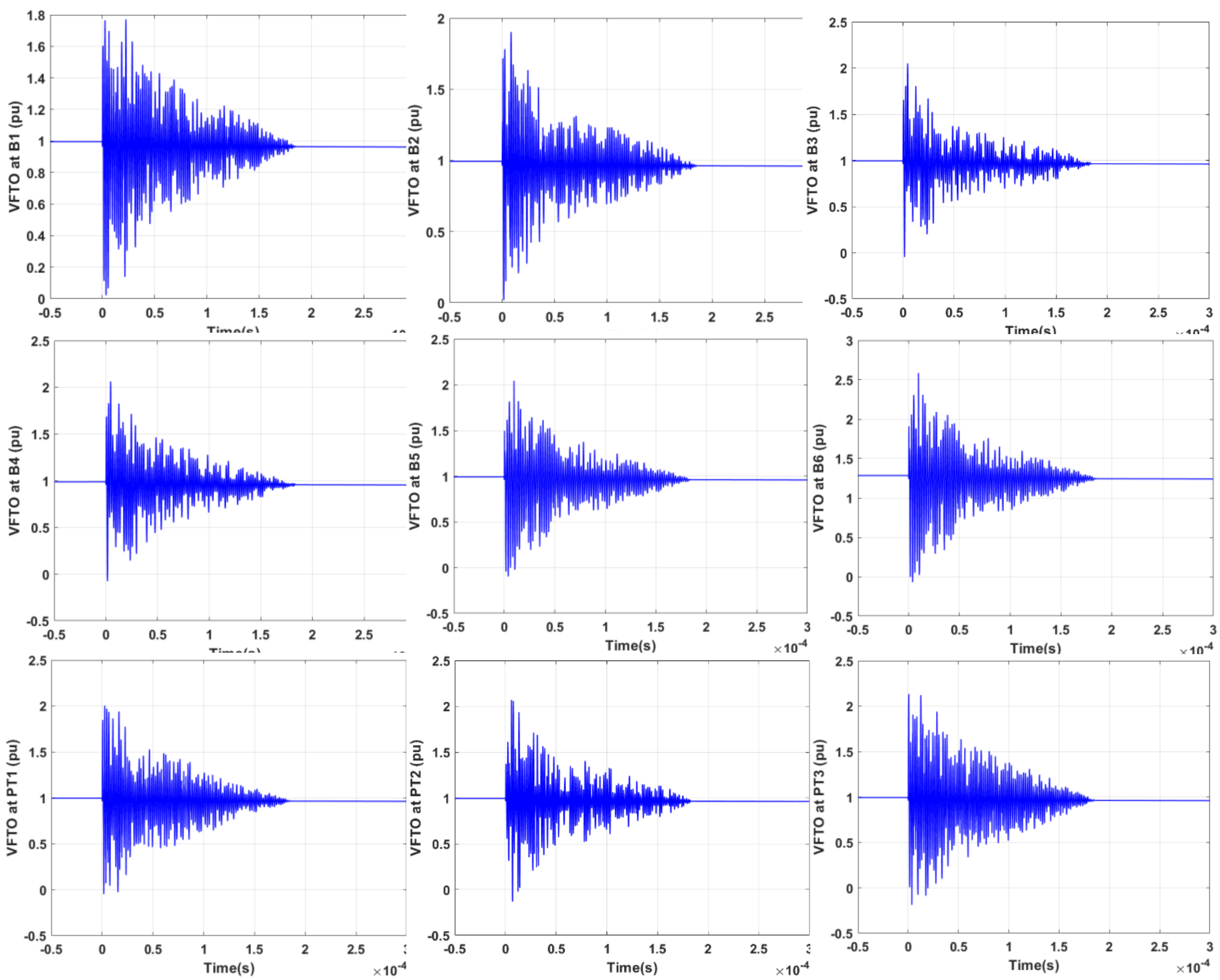


Fig 9. VFTOs at disconnector switches (CB1-CB6) and at potential transformers (PT1-PT6) of 1000 KV substation due to switching operation of CB1 disconnector switch with resistor as mitigating device



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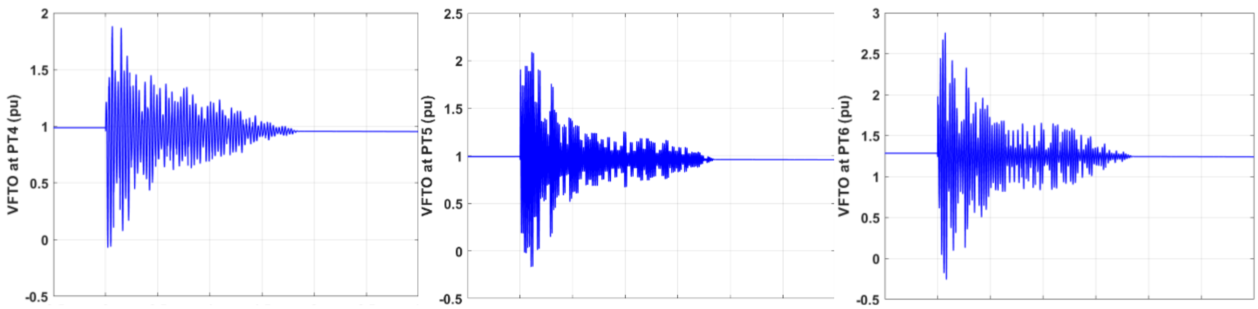

Fig 10. VFTOs at disconnector switches (CB1-CB6) and at potential transformers (PT1-PT6) of 1000 KV substation due to switching operation of CB1 disconnector switch with RC Filter as mitigating device

Table 2. VFTOs magnitude, settling time and rise time for 1000KV substation without and with mitigating device

Measured location	With additional resistance as mitigating device			With additional 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	2.7	1.33	250.1	1.78	1.185	175.6
CB2	2.38	1.21	198.3	1.82	1.172	178.36
CB3	2.55	1.29	197.5	2.03	1.183	170.36
PT1	2.5	1.32	180.3	1.9	1.169	175.9
PT2	2.55	1.29	185.0	2.03	1.185	176.35
PT3	2.58	1.28	181.56	2.1	1.182	175.8

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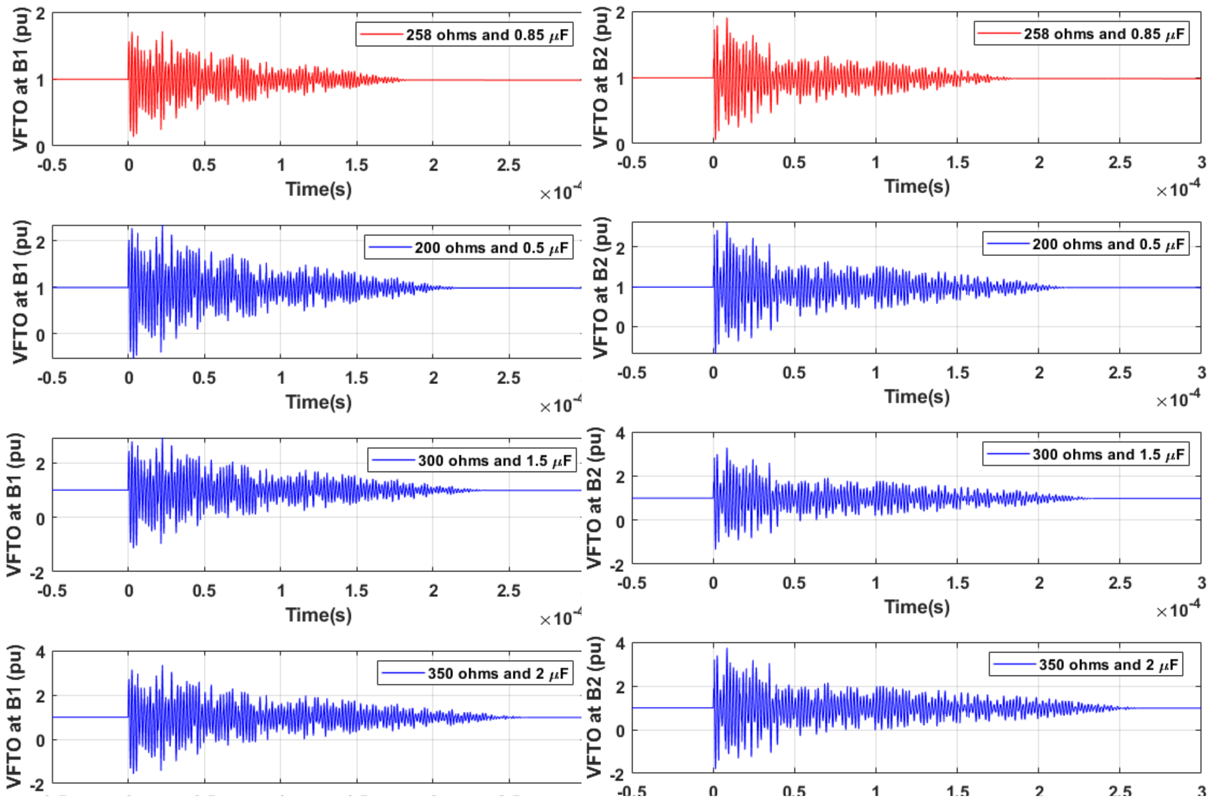

Fig 11. VFTOs at B1 and B2 locations of substation for 4 different values of RC Filter

c. Result analysis for 1200 KV substation

VFTOs at various points of 1200 KV substation shown in fig 12 and fig 13 due to switching of CB1 disconnector switch with resistance and with RC filter as mitigating devices are presented. Voltage transients at locations at disconnector switches (CB1-CB15) and at potential transformers (PT1-PT11) are shown in fig 12 with resistance and in fig 13 with RC filter. 336Ω resistance and 1.148 μF capacitance is chosen as optimized values by examining the modeled system with different values of RC filters. VFTO magnitudes and their respective settling and rise times are tabulated for CB1-CB3 and PT1-PT3 with resistance and with RC Filter. VFTOs for four different RC filters at B1 and B2 location are shown in fig 14 to check efficacy of proposed values of resistance and capacitance. After replacing resistance with RC filter as mitigating device in disconnector switch reduces voltage transient magnitudes by 10% and reduces settling time by 30-40 μ seconds. Peak magnitude of VFTOs is changing in between 1.8-2.01 p.u. with resistance and 1.6-1.78p.u. with RC filter.

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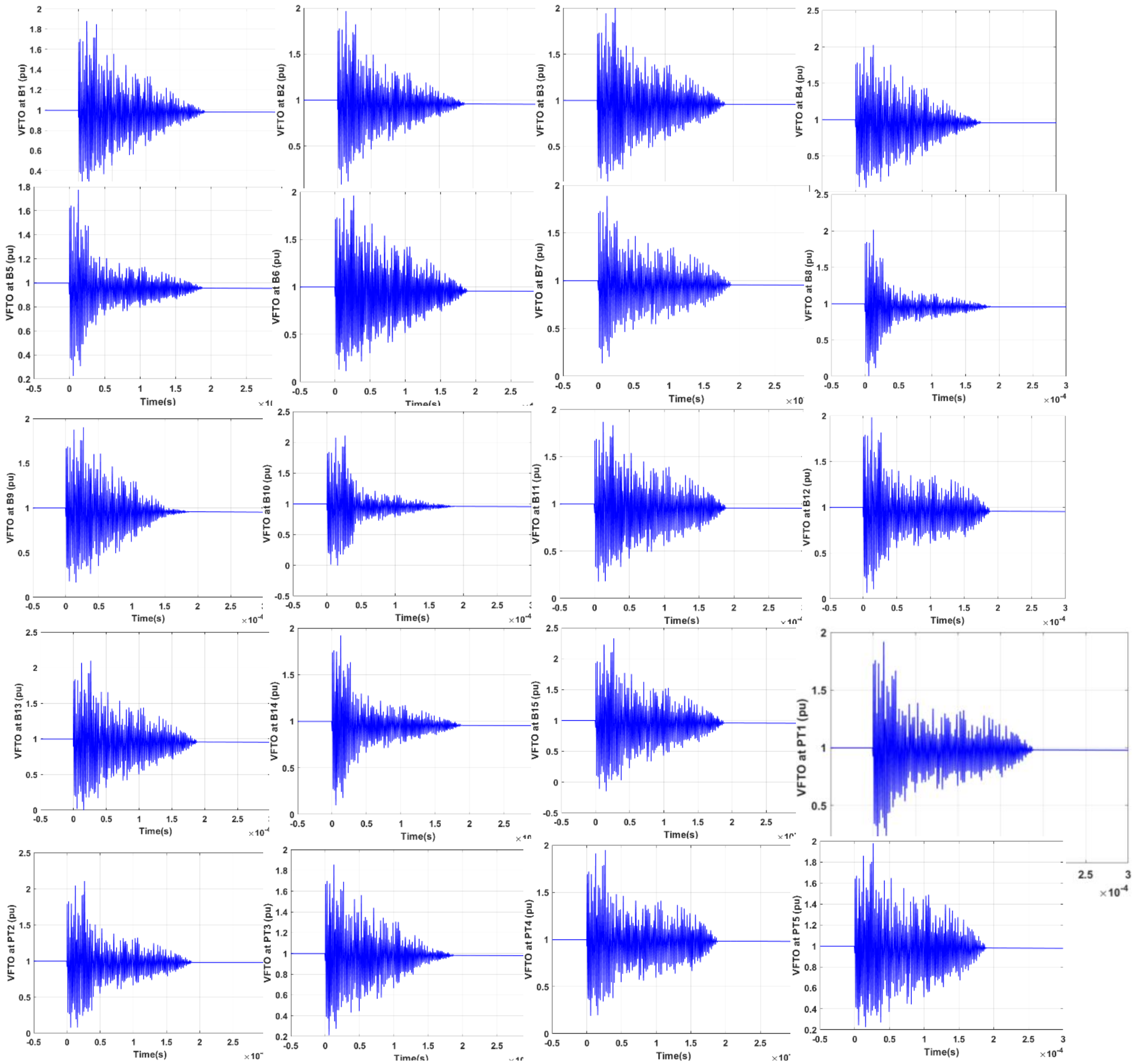

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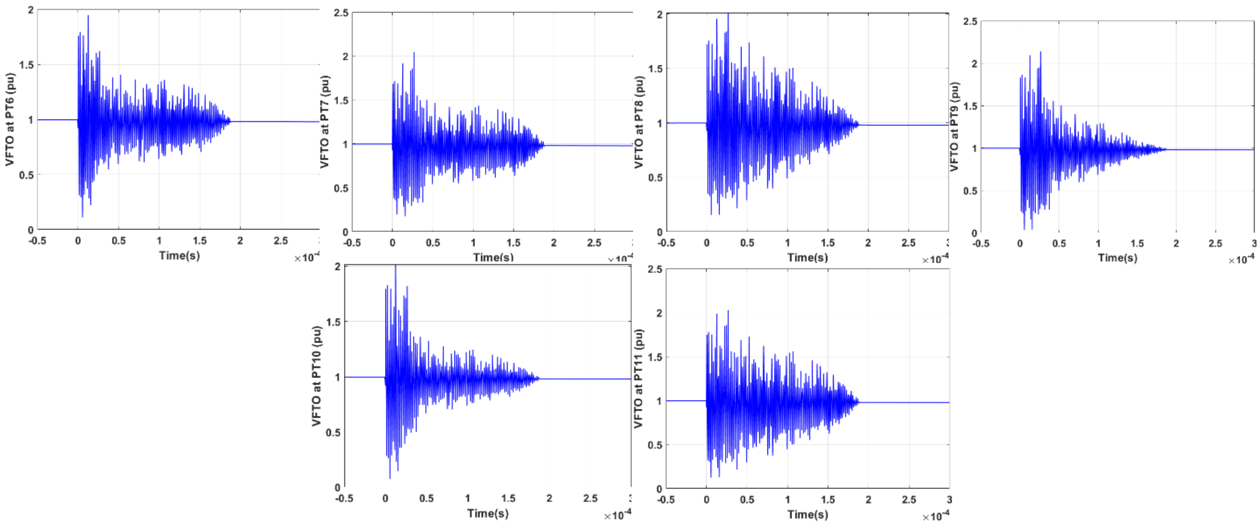
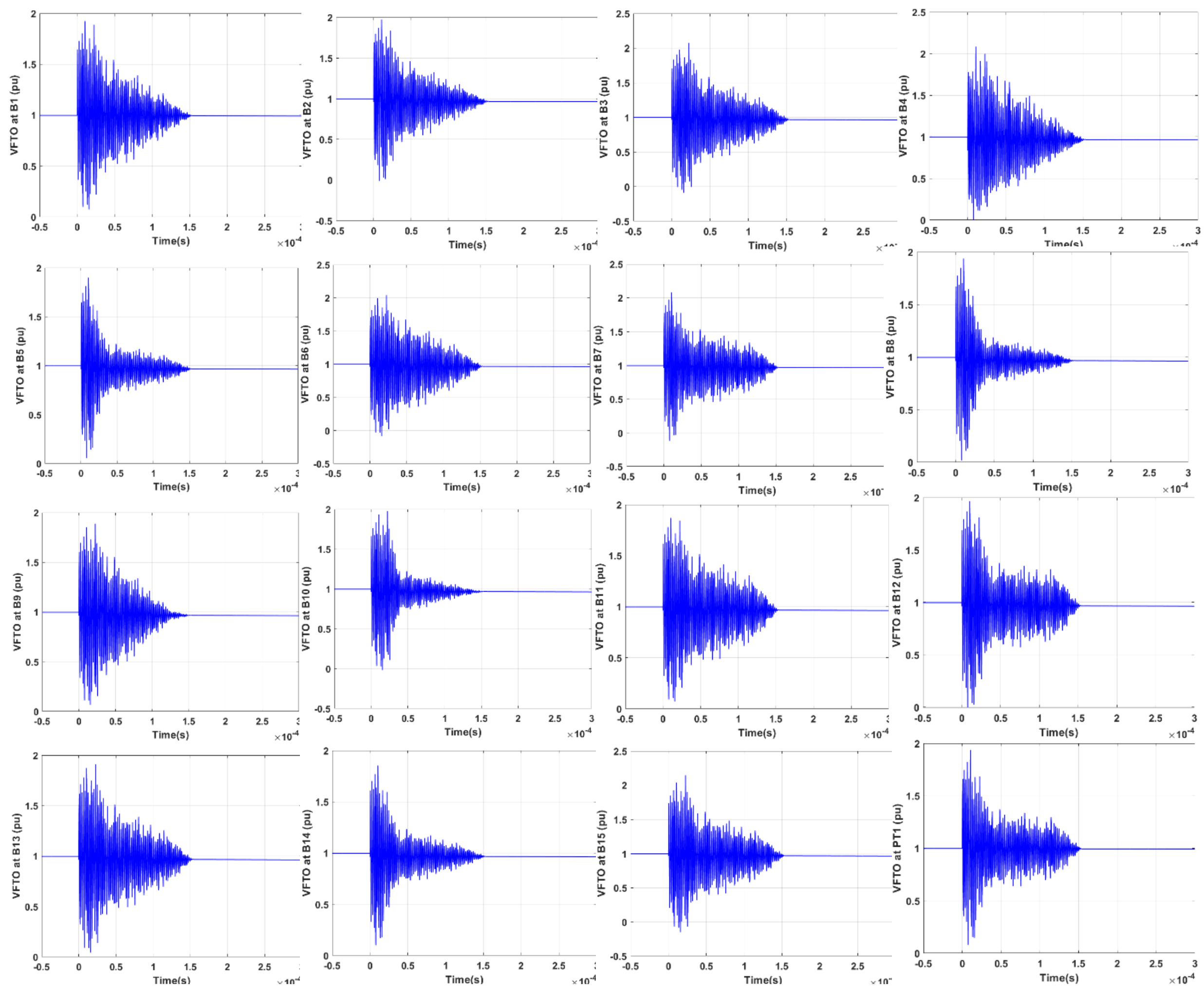


Fig 12. VFTOs at point of connection of switches (CB1-CB15) and at potential transformers (PT1-PT11) of 1200 KV substation due to switching operation of CB1 disconnector switch with resistor as mitigating device



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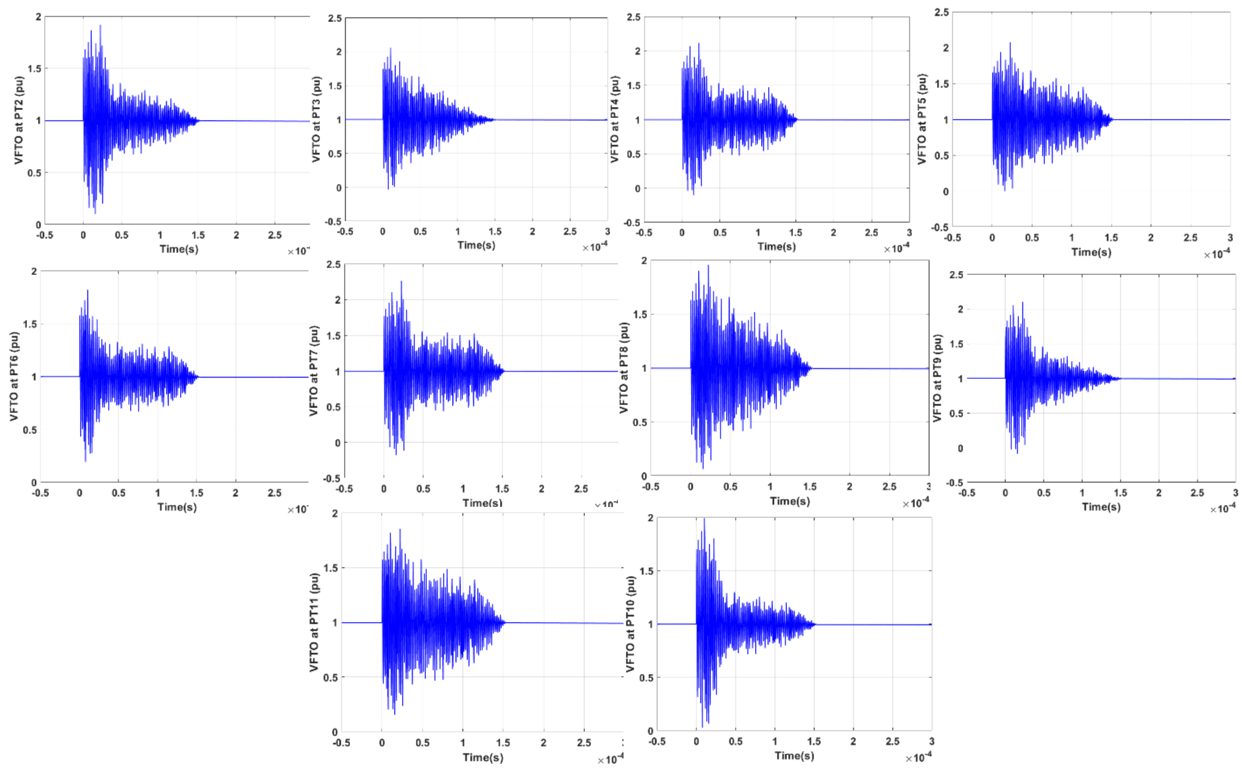

Fig 13. VFTOs at point of connection of switches (CB1-CB15) and at potential transformers (PT1-PT11) of 1200 KV substation due to switching operation of CB1 disconnector switch with RC Filter as mitigating device

Table 3. VFTOs magnitude, settling time and rise time for 1200KV substation without and with mitigating device

Measured location	With additional resistance as mitigating device			With additional 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	1.91	1.25	186.9	1.78	1.18	149.6
CB2	1.8	1.19	191.25	1.62	1.12	150.32
CB3	2.01	1.29	185.36	1.71	1.174	150.1
PT1	1.85	1.22	179.20	1.6	1.181	149.86
PT2	2.01	1.25	180.65	1.7	1.18	149.9
PT3	1.9	1.2	180.65	1.62	1.179	150.05

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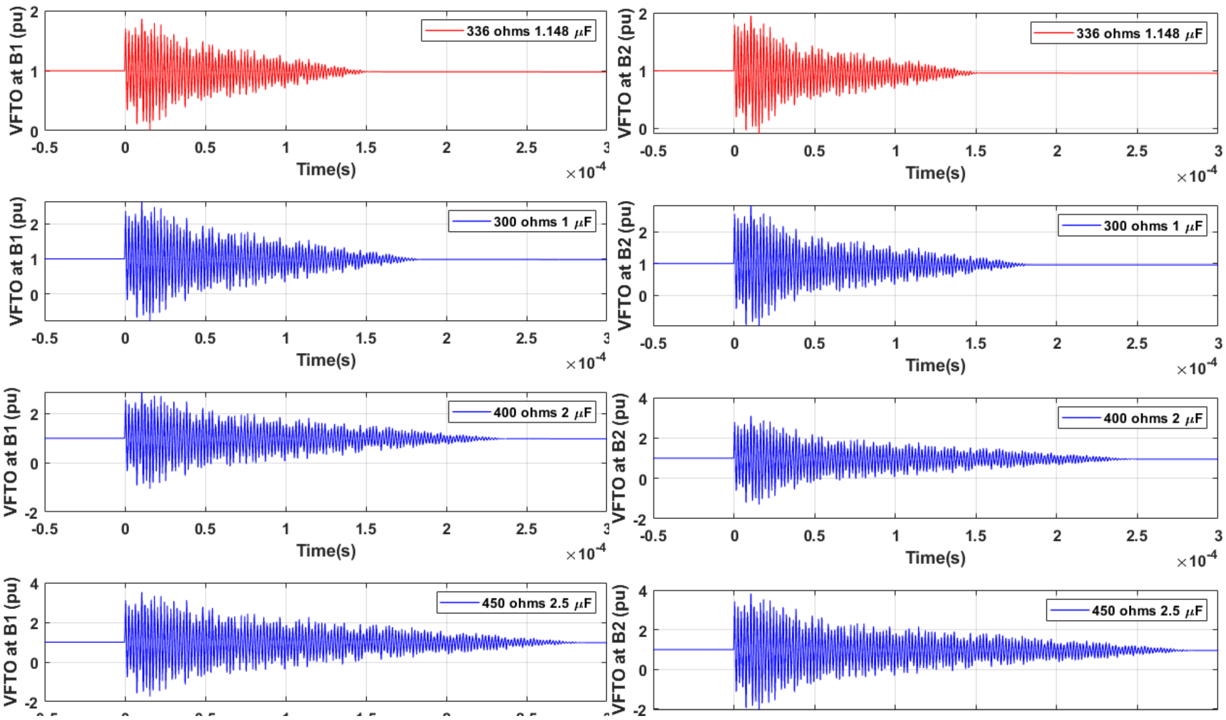
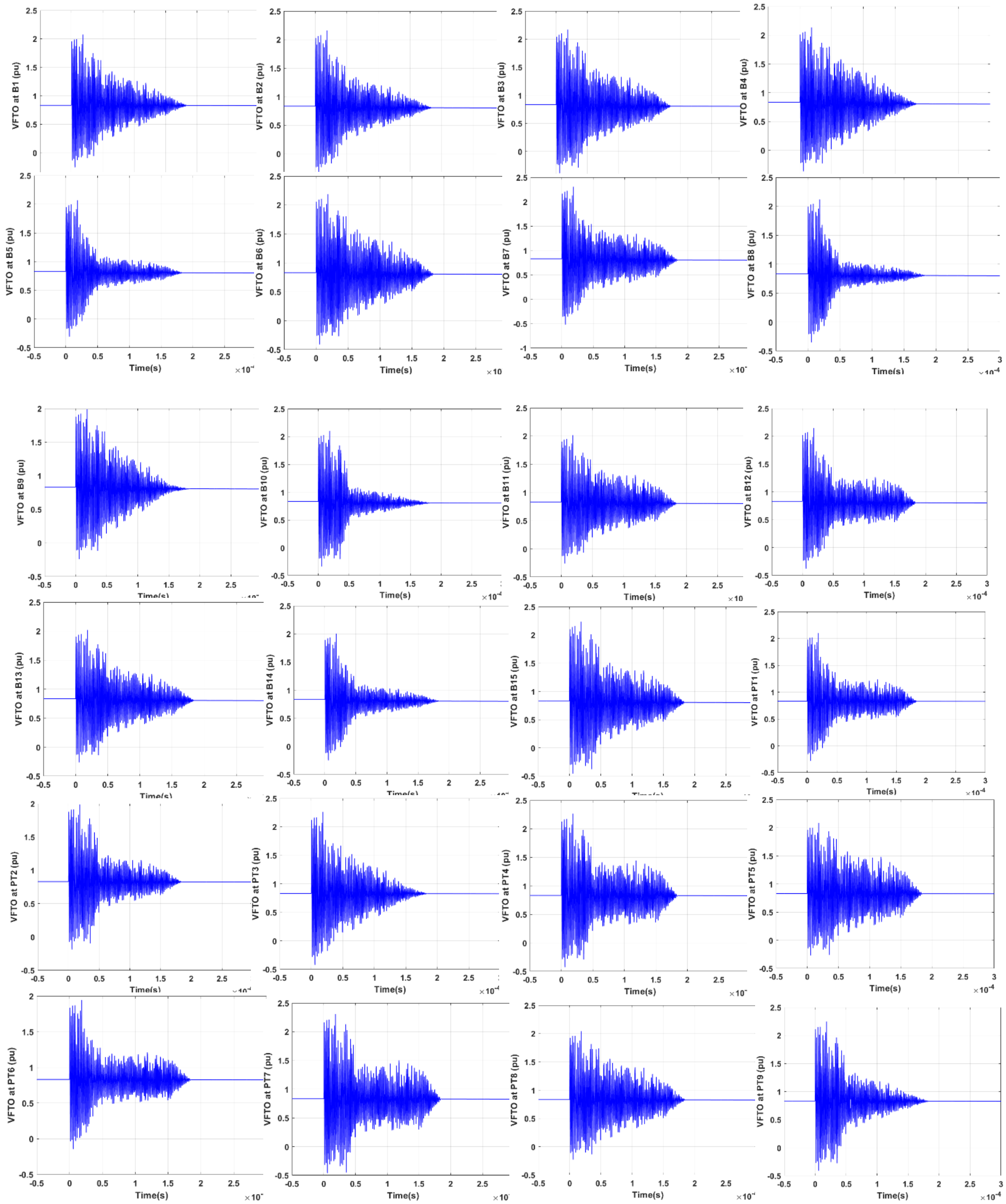


Fig 14. VFTOs at B1 and B2 locations of substation for 4 different values of RC Filter

d. Result analysis for 1500 KV substation

Voltage transient results for 1500 KV substation are presented here. Single line diagram of 1500KV substation is shown in fig 5 is modelled and simulated with resistance and with RC Filter as mitigating devices. 296 Ω resistance and 3.86 µF capacitance is chosen as optimized values by examining the modeled system with different values of RC filters. VFTO magnitudes and their respective settling and rise times are tabulated for CB1-CB3 and PT1-PT3 with resistance and with RC Filter. VFTOs for four different RC filters at B1 and B2 location are shown in fig 15 to check efficacy of proposed values of resistance and capacitance. After replacing resistance with RC filter as mitigating device in disconnector switch reduces voltage transient magnitudes by 16% and reduces settling time by 40-50 µ seconds. Peak magnitude of VFTOs is changing in between 2.01-2.1 p.u. with resistance and 1.72-1.9 p.u. with RC filter.


VFTO at B1 (pu)
VFTO at B2 (pu)
VFTO at B3 (pu)
VFTO at B4 (pu)
VFTO at B5 (pu)
VFTO at B6 (pu)
VFTO at B7 (pu)
VFTO at B8 (pu)
VFTO at B9 (pu)
VFTO at B10 (pu)
VFTO at B11 (pu)
VFTO at B12 (pu)
VFTO at B13 (pu)
VFTO at B14 (pu)
VFTO at B15 (pu)
VFTO at PT1 (pu)
VFTO at PT2 (pu)
VFTO at PT3 (pu)
VFTO at PT4 (pu)
VFTO at PT5 (pu)
VFTO at PT6 (pu)
VFTO at PT7 (pu)
VFTO at PT8 (pu)
VFTO at PT9 (pu)
Time(s)
$\times 10^{-4}$

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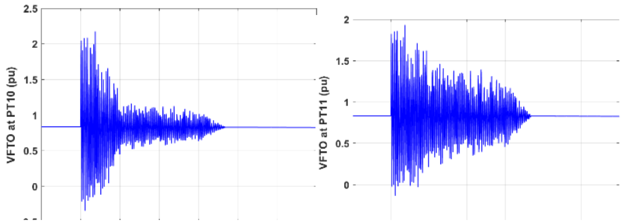
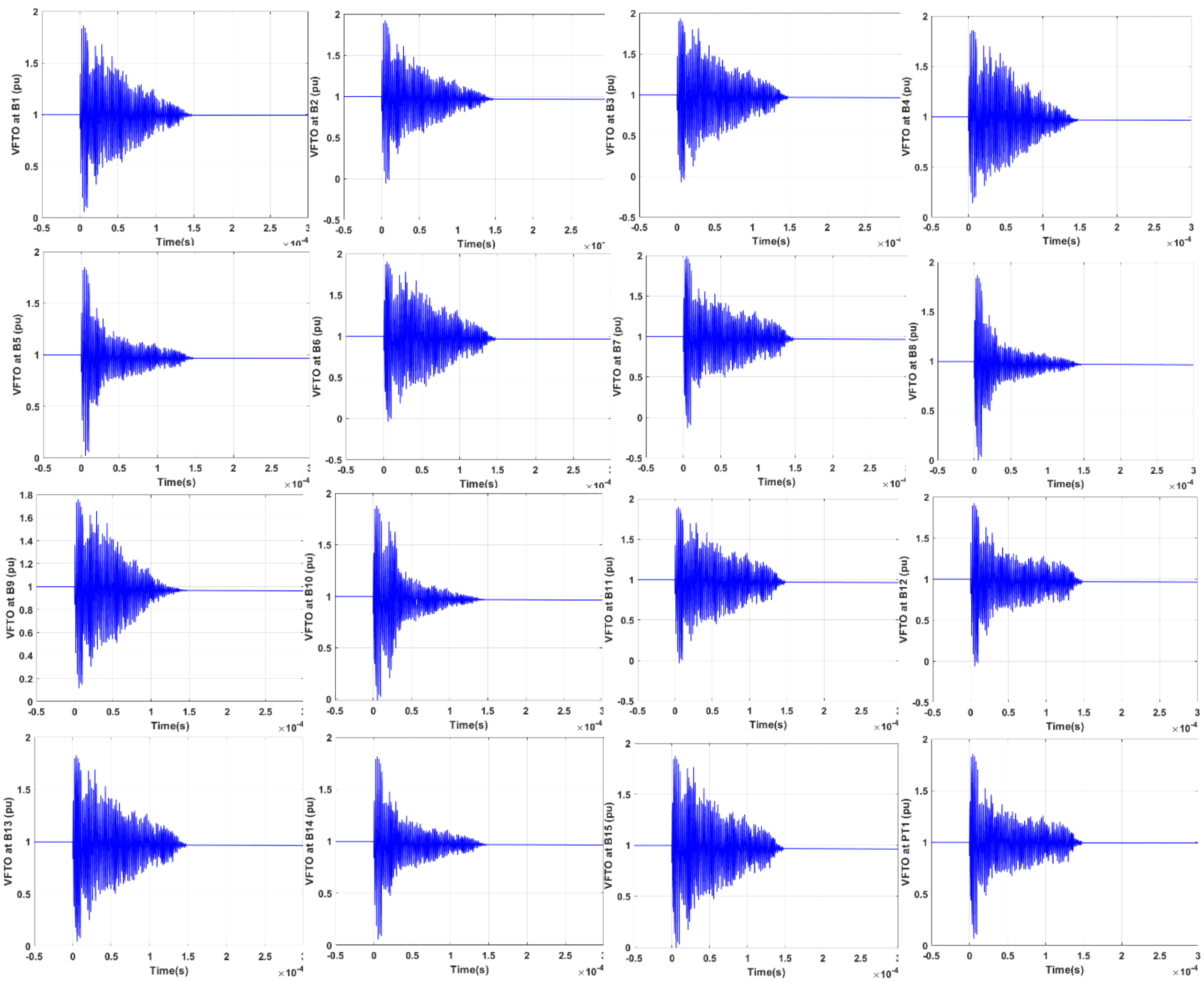


Fig 15. VFTOs at point of connection of switches (CB1-CB15) and at potential transformers (PT1-PT11) of 1500 KV substation due to switching operation of CB1 disconnector switch with resistance as mitigating device



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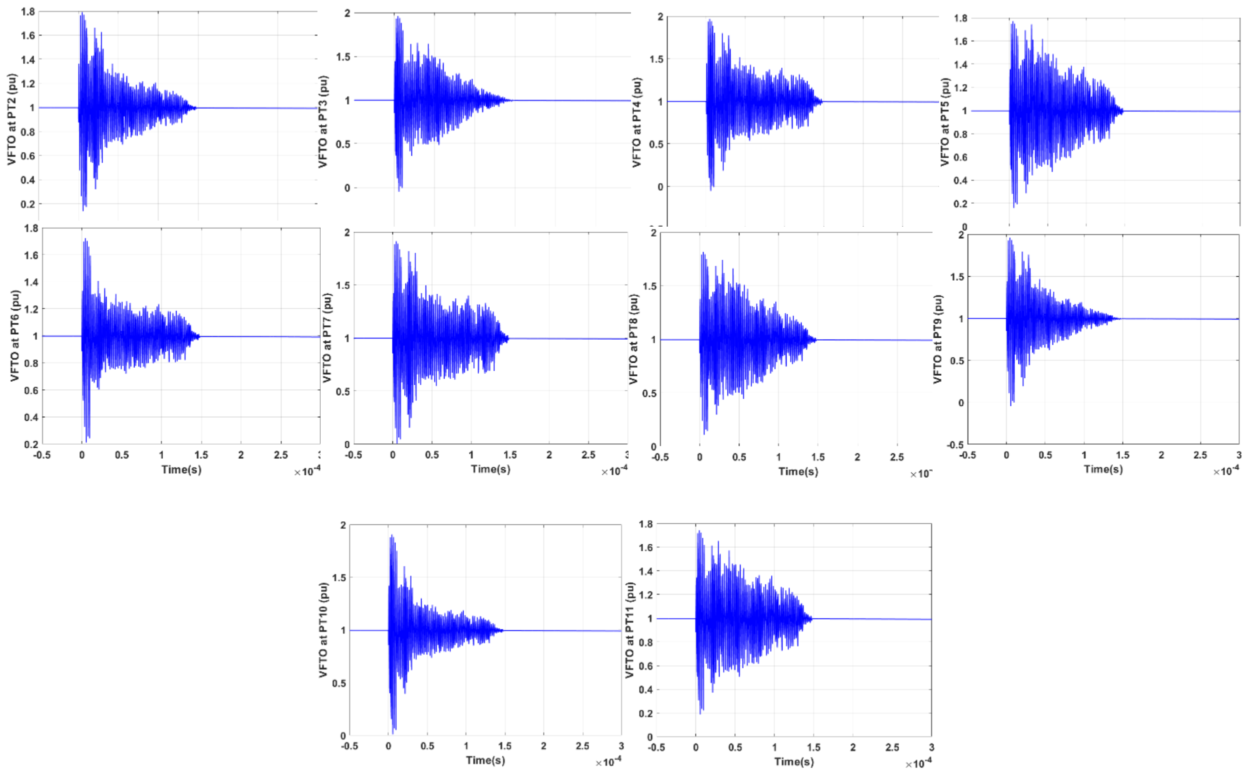

Fig 16. VFTOs at point of connection of switches (CB1-CB15) and at potential transformers (PT1-PT11) of 1500 KV substation due to switching operation of CB1 disconnector switch with RC Filter as mitigating device

Table 4. VFTOs magnitude, settling time and rise time for 1500KV substation without and with 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	2.05	1.18	185.1	1.72	1.18	140.56
CB2	2.1	1.16	181.5	1.81	1.16	141.2
CB3	2.1	1.20	183.6	1.8	1.20	141.15
PT1	2.05	1.21	160.1	1.7	1.21	145.23
PT2	2.0	1.24	159.23	1.78	1.24	144.6
PT3	2.01	1.2	159.8	1.9	1.2	145.8

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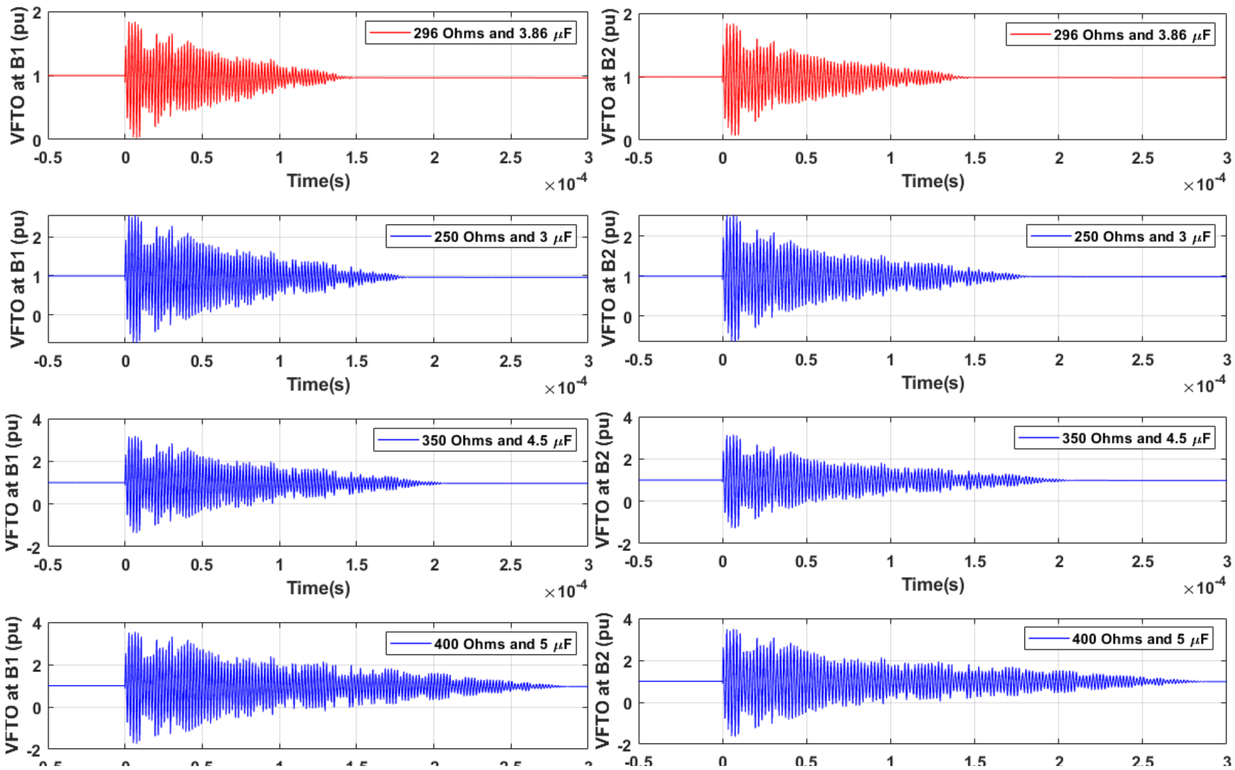

Fig 17. VFTOs at B1 and B2 locations of substation for 4 different values of RC Filters

V. Conclusion

RC Filter based mitigation of very fast transient over voltages in gas insulated switchgear substation is proposed in this paper. Appropriate modelling techniques are adopted to analyze VFTOs due to switching events of disconnector switches. Four ultrahigh voltage rated substations are chosen to analyze. Mitigation technique of VFTOs based on RC Filter with disconnector switch is proposed for GIS by considering voltage magnitudes at their respective locations and to optimize filter values for mitigation. Simulation results are presented for voltage transients during switching operation of disconnector switch with resistor and with RC Filter as mitigating devices. Optimized RC filter values are compared with other values to check efficacy of proposed values. Magnitude of VFTOs and settling times at different locations of substations are tabulated. From results It was clear that the first amplitude of the VFTO was mitigated from 10-35% and settling times are reduced by 30-50 µseconds.

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