Computation of Very Fast Transient Overvoltages (VFTO) in a 1000 kV Gas Insulated Substation

M. A. Haseeb and M. Joy. Thomas
Department of Electrical Engineering
Indian Institute of Science
Bangalore, India

***Abstract*—Very fast transient overvoltages (VFTO) generated in a gas insulated substation (GIS) during disconnector switching operations is one of the major concerns in insulation design of the GIS. Such over voltages can cause malfunctioning of the protection and control circuits in addition to initiating faults inside the gas insulated bus ducts of the substation especially in the presence of metallic particles. In this paper, VFTO have been estimated at various points in a 1000 kV rated substation for all possible valid disconnector switching operations. For the substation studied, the maximum computed overvoltage is 1.58 pu without considering the trapped charge on the busbar. Major frequency components in the simulated VFTO lies in the range of 840 KHz to 30 MHz. Simulations have been carried out using the Electromagnetic Transient Program (EMTP).**

***Keywords*: Gas Insulated Substation (GIS), Electromagnetic Transient Program (EMTP), Very Fast Transient Overvoltage (VFTO), Ultra high voltage (UHV) substation.**

I. Introduction

In the past few decades gas insulated substations have gained wider acceptance among the power utilities due to its easy maintenance, requirement of less space, high reliability and good environmental adaptability [1][2]. Inspite of the several advantages, there are several issues of concern in a GIS. One such issue is the generation of VFTO during disconnector operations. The rapid collapse of voltage due to breakdown of the SF_6 gas generates steep-fronted travelling waves, which propagate from the source in both directions. These travelling waves propagate throughout the GIS with little attenuation, and distortion. Disconnector switching induced transients produce complex waveforms by reflection and transmission at substation discontinuities [1]-[5]. Accurate estimation of the amplitude and rise time is made possible in the recent years by advancements in analysis techniques and availability of softwares such as EMTP. Rise time of the VFTO is in the order of few ns and hence requires detailed modeling of the substation components for reliable estimation of the overvoltage parameters.

Ultrahigh voltage (UHV) technology has received good attention in the past few years and few systems have been installed already in various parts of the world. Long distance UHV lines lead to reduction in power loss and reduction in reactive power consumed by the line [6][7].

Per unit magnitude of the impulse withstand voltage decreases with increasing system voltage. As the rated voltage increases, the difference between the rated lightning impulse withstand voltage (LIWV) and the VFTO decreases. Hence, VFTO may become important for dielectric dimensioning at UHV voltage levels [7].

Origin of VFTO is mainly due to the slow speed disconnector switching operations. The fast break down nature of SF_6 gas leads to fast risetime travelling waves which gets reflected and transmitted at substation discontinuities leading to generation of complex wave shapes. These surges lead to overvoltages at various points in the substation and may result in insulation failure. The transient enclosure voltage (TEV) developed on the grounded enclosure due to the reflection and transmission at the enclosure-bushing junction can cause damages in secondary control circuits [1][8]. Earth fault in disconnector due to sudden change in field configuration which occurs at the moment of arc completion across the contacts is also one of the major concerns [9].

The risetime t_r of these surges can be obtained by the following equation

$$t_r = 13.3 \frac{k_T}{\Delta u / s} \qquad (1)$$

Where k_T is the Teopler spark constant and is equal to 50 kVns/cm, D*u* is the voltage between the disconnector terminals just preceding the voltage collapse in kV, and s is the spark length in cm [1].

II. Description of the System and Modeling

A. *Description of the system under study*

For the present study a 1000 kV UHV system whose single line diagram is as shown in Fig. 1 has been used. The transmission line is 636 km long and the system consists of four GIS substations ‘A’, ‘B’, ‘C’ and ‘D’. The substation considered for the present study is substation ‘A’. Detailed substation structure is shown in Fig. 2. T1 and T2 in Fig. 2 are UHV transformers of rated capacity 1000/1000/334 MVA, rated voltage of 1050/525/110 kV. There are six surge arresters in the system named F1 to F4, MOA1 and MOA2. F1 and F3 are arresters for transformers and F2 and F4 are arresters at the entrance of transmission lines. CB1 to CB6 are the circuit breakers, PT3 and PT4 are the potential transformers in the system. PT1, PT2, PT5 and PT6 are the

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capacitive voltage transformers in the system. Locations of the disconnectors are not shown to avoid cluttering of the figure. However, the same is shown in the detailed diagram of a portion of the substation in Fig. 3.

B. *Modeling of the system under study*

Electromagnetic Transient Program (EMTP) is used for the simulation of VFTO. Busbar is modeled by a distributed parameter transmission line whose characteristic impedance is given by the equation

$$Z = 60\ln\left(\frac{b}{a}\right) \qquad (2)$$

Where 'b' and 'a' are the inner diameter of the busbar enclosure and diameter of center conductor respectively. The characteristic impedance is 95 Ω for the substation bus ducts studied.

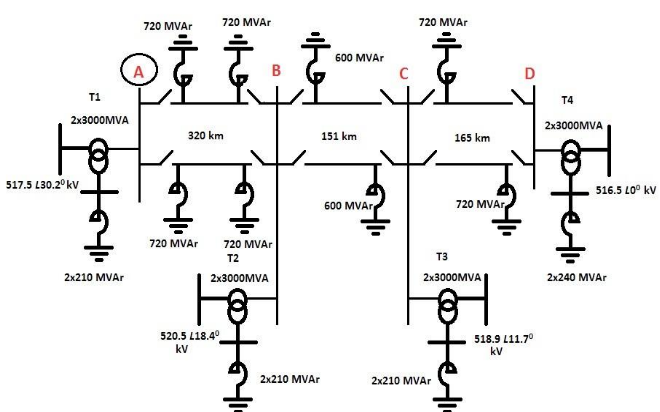


Figure 1. Single line diagram of the 1000 kV Ultra High Voltage power transmission system [6]

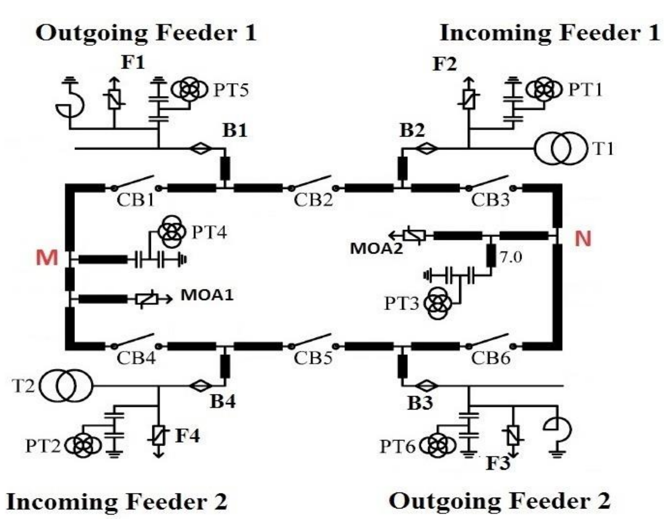


Figure 2. Schematic diagram of the 1000 kV substation 'A' (unit of length: in meters) [5]

The surge arrester is modeled by a nonlinear resistor with voltage-current characteristics as presented in Table I [5][6].

PT1, PT2, PT5 and PT6 are modeled with lumped capacitance of value 5000 pF where as PT3 and PT4 are modeled by lumped capacitance of 1000 pF [5].

Transformer: The basic model of all the transformers uses the parameters mentioned in section A. To approximate the high-frequency characteristics, additional capacitors of 5000 pF are paralleled at the entry of the transformers [5]. Transformer saturation is ignored.

The 320 km long transmission line is modeled by a distributed parameter transmission line terminated with a resistor having resistance same as that of the characteristic impedance of the line to avoid reflection. Hence the transmission line model used in the present work is not a frequency dependent model.

Arc resistance: Dynamic arc resistance model is used and is given by the following equation

$$R = r + R_0 e^{-\frac{t}{T}} \qquad (3)$$

Where R_0 is initialized to a very high value 10^{12} Ω and r is the residual series resistance and is taken as 0.5 Ω [10]. Modeling of other GIS components is as shown in Table II.

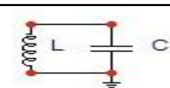
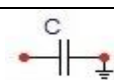
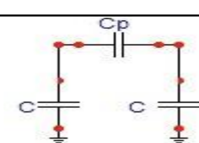
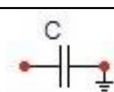
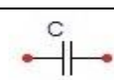
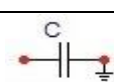
TABLE I

V-I Characteristics of the Metal Oxide Arresters [5]

Current (A)	0.008	2 000	10 000	20 000
Voltage (kV)	1114	1460	1553	1620

TABLE II

Model used and values of various GIS components rated for 1000 kV [5]

Component	**Equivalent model**	**Equivalent parameter**
Shunt reactor		C=4000 pF 720 MVAr
Circuit breaker (closed)		C=300 pF
Circuit breaker (opened)		C=108.6 pF C_p=.605 nF
Disconnector (closed)		C=80 pF
Disconnector (opened)		C=4.5 pF
SF_6-Oil bushing		C=320 pF

III. EMTP SIMULATION AND RESULTS

The time step used in the simulation must be at least 10 times less than the travel time of the shortest bus section in the system which is about 1 ns in the present case. Only one phase of the substation is modeled in Electro Magnetic Transient Program for the present simulation because, the switching operation and the corresponding VFTO phenomena are same in the other two phases. In addition, it is assumed that an isolated phase bus duct arrangement is being used and hence the intra-phase coupling is assumed to be negligible. The system is assumed to be at steady state prior to the switching operation and each disconnector switching is performed when the sinusoidal power frequency voltage is at its peak. The disconnectors associated with each of the six circuit breakers are operated one by one and the amplitude of VFTO at various locations is computed. Due to symmetry in the system, only half the number of disconnector operations need to be studied. The small bus section between the circuit breaker and the disconnector may have trapped charge and will increase the peak of the transient over voltage. In the present simulation trapped charge is not taken in to account. Also in the present work, transient simulations have been carried out without any load connected to the system. Measuring points include all the circuit breakers, surge arresters, potential transformers and the disconnector which is under operation.

The location of the disconnectors is not shown in Fig. 2. So the upper part of the UHV substation is enlarged from location 'M' to 'N' (see Fig. 2) and is shown in Fig. 3. Note that '+' in the circuit breaker denotes the terminal at which incoming feeder is connected and '-' denotes terminal which is connected towards the outgoing feeder. Overvoltage at the circuit breaker terminals when the disconnector on the left side of CB1 (denoted as DS1 in Fig. 3) is operated is shown in Fig. 4. Magnified waveform of the transient overvoltage at the terminal of CB1 near the operating disconnector DS1 (denoted as CB1+) in time domain is shown in Fig. 5(a) and its frequency domain waveform is shown in Fig. 5(b). From the Fig. 5, the peak value of the VFTO is found to be 1.50 pu. The corresponding rise time is 40 ns. The dominant frequency component is 1.66 MHz and the highest frequency is around 38 MHz.

Similar studies are conducted at various points for the above disconnector operation and the peak value and rise time of the VFTO are tabulated in Table III. Over voltage with highest peak occurs when the disconnector at the right side of CB1 (denoted as DS2 in Fig. 3) and the disconnector at the left side of CB3 (denoted as DS5 in Fig. 3) is operated (trapped charge has not been taken into account). Peak value of 1.58 pu is observed at CB1- for the closing operation of DS2 (see Fig. 6) and at CB3+ for the closing operation of DS5 (see Fig. 9). Overvoltage at the circuit breaker terminals when the disconnector on the left side of CB3 (denoted as DS5 in Fig. 3) is operated is shown in Fig. 7. Switching operation of the remaining three disconnectors (DS3, DS4 and DS6 as shown in Fig. 3) has also been done and the parameters such as peak VFTO and rise time are tabulated.

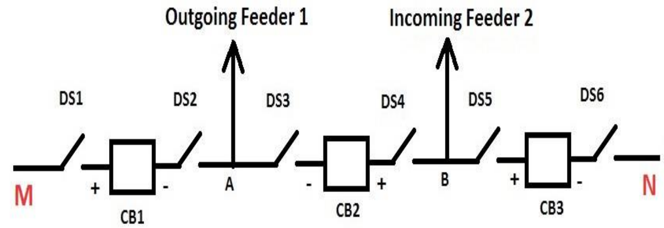


Figure 3. Single line diagram of one side of the UHV substation.

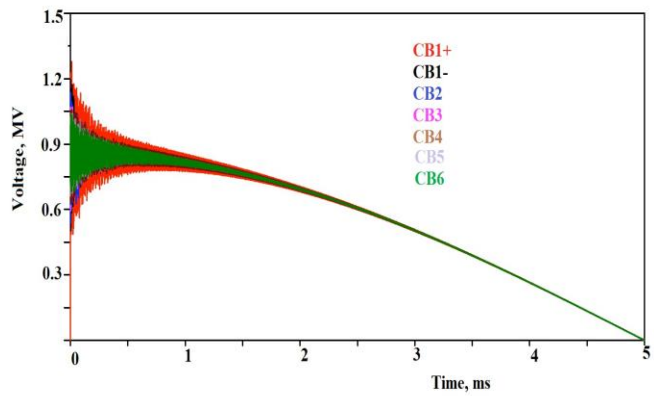
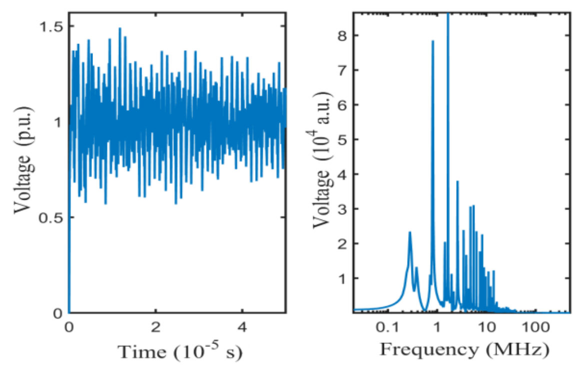
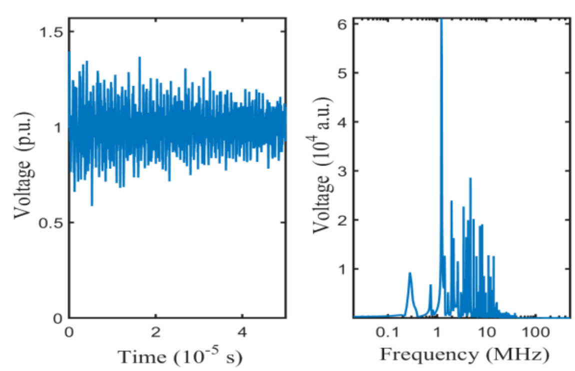


Figure 4. VFTO waveforms at six circuit breaker points for the closing operation of disconnector 1 (DS1)



(a) (b)

Figure 5. Magnified VFTO waveform at the terminal of CB1+ for the closing operation of DS1 in (a) time domain and (b) frequency domain



(a) (b)

Figure 6. Magnified VFTO waveform at the terminal CB1- for the closing operation of DS2 in (a) time domain and (b) frequency domain

TABLE III

Risetime and peak value of VFTO at different locations during operation of the disconnector-1 (DS1)

Measuring point	Rise time (ns)	Peak of VFTO (pu)
CB1+	40	1.50
CB1-	35	1.40
CB2	46	1.33
CB3	57	1.25
CB4	48	1.24
CB5	75	1.22
CB6	70	1.21
DS1	8	1.40
DS2	43	1.44
DS3	41	1.35
DS4	53	1.31
DS5	50	1.25
DS6	59	1.30
MOA1	12	1.38
MOA2	60	1.31
PT3	145	1.20
PT4	127	1.35
PT6	221	1.08

The peak VFTO at a CB1 for the closing operation of DS5 (as shown in Fig. 8) is found to be lower than the nearest measuring points CB3+ and CB3-. The peak of VFTOs generated around the entire substation show a distribution as shown in Fig. 11 and 12. On the x axis, different observation points in the UHV substation are indicated. A total of 19 observation points are selected. It is advised to refer both Fig. 2 and 3 for identifying the actual position of each measurement location. Fig 11(a) shows the peak VFTO distribution for switching operation of DS1.

The maximum peak values are observed at the nearest circuit breaker terminal. The peak distributions are identical with respect to the operating disconnector. For the switching operation of DS2, DS3, DS4, DS5 and DS6 peak VFTO distributions are as shown in Fig. 11 (b), 11(c), 11(d), 12(a) and 12(b) respectively.

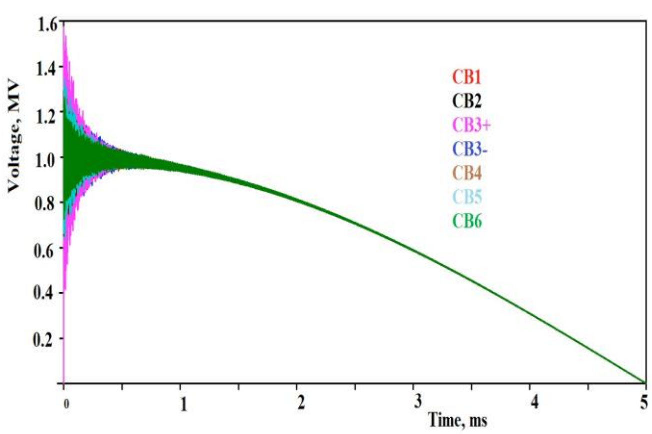
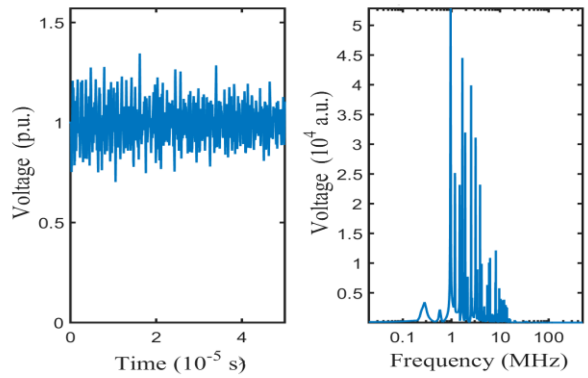
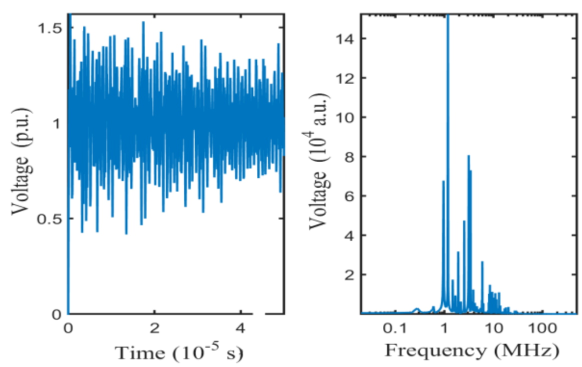


Figure 7. VFTO waveforms at six circuit breaker locations for the closing operation of disconnector 5 (DS5)



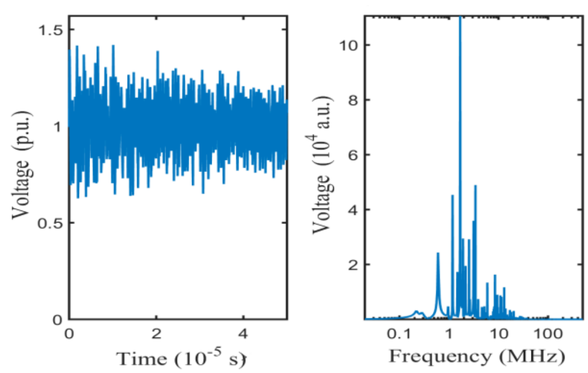
(a) (b)

Figure 8. Magnified VFTO waveform at the terminal CB1 for the closing operation of DS5 in (a) time domain and (b) frequency domain



(a) (b)

Figure 9. Magnified VFTO waveform at the terminal CB3+ for the closing operation of DS5 in (a) time domain and (b) frequency domain



(a) (b)

Figure 10. Magnified VFTO waveform at the terminal CB3- for the closing operation of DS5 in (a) time domain and (b) frequency domain

The dominant frequency components of VFTO at all measurement locations lie from 840 KHz to 30 MHz. Among all the six disconnector switching operations and nineteen observation points considered, the lowest peak is obtained at PT6. Because, (i) due to the long transmission line ahead (which is modeled as an infinite line), there will be no reflection. This leads to less enhancement of VFTO. (ii) The capacitive voltage transformer and the shunt reactor at the line end are modeled by large capacitance values. This leads to slow rise of transients.

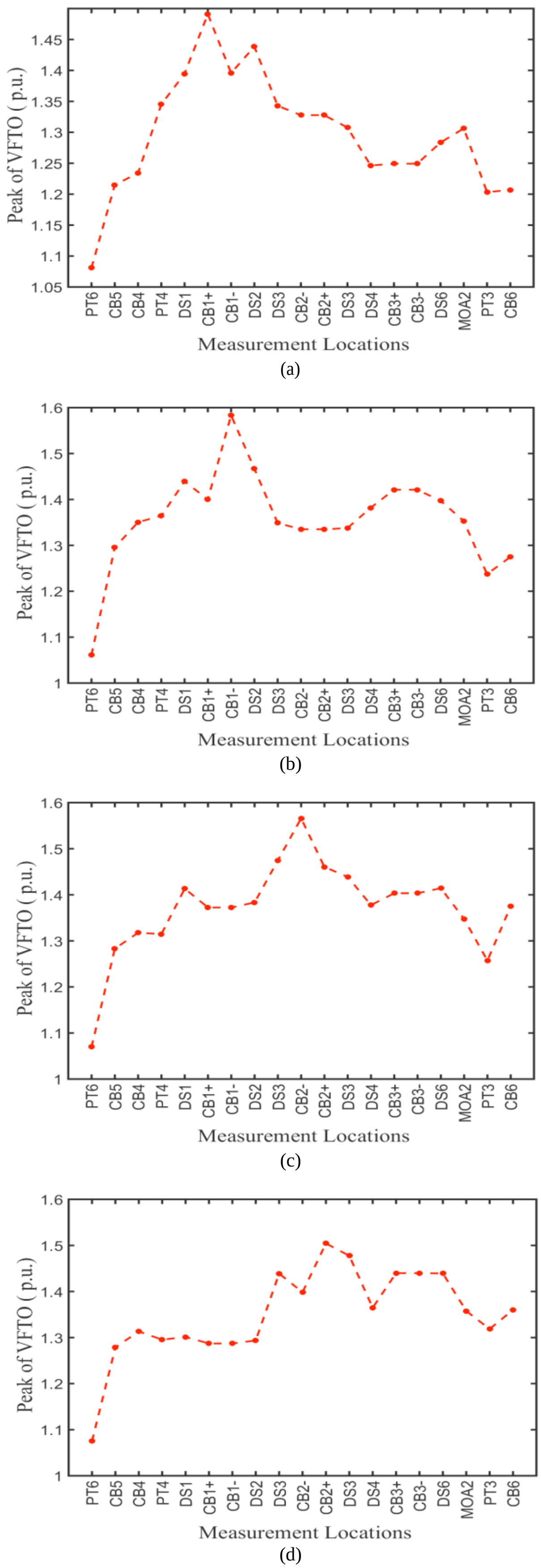


Figure 11. VFTO peak distribution around the substation for the closing operation of (a) DS1 (b) DS2 (c) DS3 (d) DS4

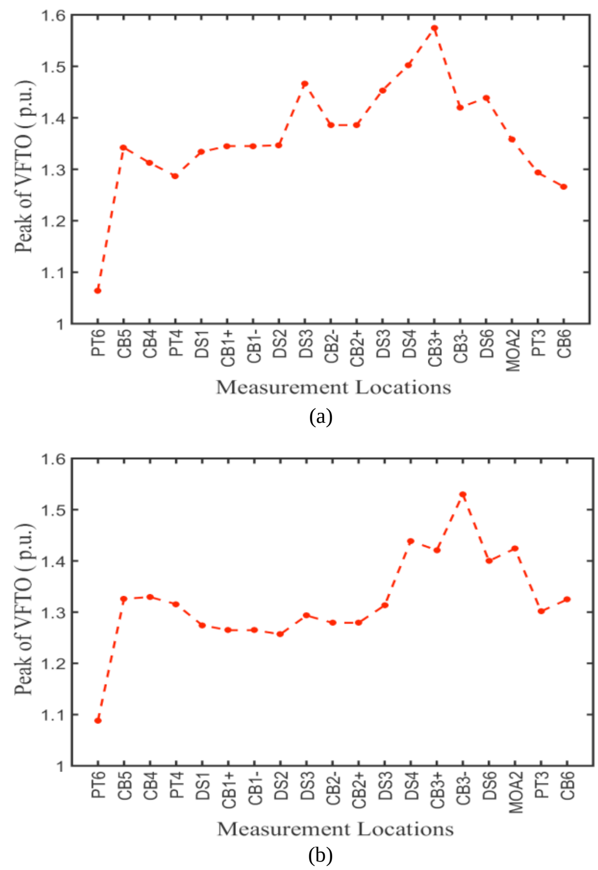


Figure 12. VFTO peak distribution around the substation for the closing operation of (a) DS5 (b) DS6

IV. Conclusions

From the detailed study of the VFTO generated due to disconnector switching operation in the 1000 kV UHV substation, following conclusions can be made.

- The maximum VFTO among all the nineteen measuring points is 1.58 pu at CB1- for the closing operation of disconnector DS2 and at CB3+ for the closing operation of DS5 without considering the trapped charge. Since most disconnectors are of slow speed, the trapped charge in the bus section does not exceed 0.3 pu. So by taking trapped charge into account, peak of VFTO may go up to 2 pu.
- From the Fast Fourier Transform (FFT) analysis of all the 120 simulated VFTO waveforms, the frequency components observed are from 840 KHz to 70 MHz and the dominant frequency components are from 840 KHz to 30 MHz.
- In all the disconnector switching operations, the minimum peak value is observed at PT6 because of zero reflection from the transmission line side.

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