

# STUDY OF FAST TRANSIENTS GENERATED IN A GIS BUS DUCT IN COMPRESSED SF<sub>6</sub>-N<sub>2</sub> GAS MIXTURES CONTAINING LOWER PERCENTAGES OF SF<sub>6</sub>

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## ABSTRACT

This paper deals with the study of Very Fast Transient Overvoltages (VFTO) with SF<sub>6</sub>-N<sub>2</sub> gas mixture as the insulating medium, but with lower percentages of SF<sub>6</sub> in the mixture. The investigations are performed using a laboratory model bus duct. A capacitive voltage sensor was used to measure the peak VFTO and temporal characteristics. Measurements were carried out in SF<sub>6</sub>-N<sub>2</sub> gas mixtures wherein the concentration of SF<sub>6</sub> was varied from 0 to 20% over a pressure range of 1 to 5 bars. The results are then compared with those obtained for pure SF<sub>6</sub>. The VFTO characteristics obtained for SF<sub>6</sub> and SF<sub>6</sub>-N<sub>2</sub> mixtures show similar trends in variations. The levels of surge peak magnitudes are less than 2.0 p.u. in the experimental pressure range in all the cases. In N<sub>2</sub>, the VFTO level remains almost constant with increase in pressure whereas in the case of mixtures, the VFTO level was found to increase with increase in pressure as well as with increase in the percentage of SF<sub>6</sub> in the mixture. In mixtures, no significant difference in the VFTO levels is seen between 2-4 bars, although this fact is more pronounced at percentages of SF<sub>6</sub> higher than 5%. This can be attributed to the occurrence of corona stabilization in the breakdown process.

## INTRODUCTION

During switching operations or earth faults in a Gas Insulated Switchgear (GIS), steep fronted transients are generated which stress the equipment in GIS adjacent to the air insulated parts and those located nearby [1, 2]. At each irregularity of the characteristic impedance inside the GIS and its interfaces with other equipments, these transients are reflected and superimposed on the steady state voltage. Although these waves have a frequency band in a real GIS, a single frequency voltage shape has been used to evaluate their effect on the dielectric behavior of the components in the GIS [3].

SF<sub>6</sub> is the main mode of insulation in a GIS. However, in recent years, the future use of SF<sub>6</sub> has been debated throughout the world in spite of it having all the desirable properties of a good insulating and arc-quenching medium. This is because SF<sub>6</sub> has been found to be a greenhouse gas contributing to the global warming of the atmosphere. Also, highly toxic and corrosive compounds are formed when SF<sub>6</sub> is subjected

to an electrical discharge. In this regard, investigations are in progress to evolve substitutes for SF<sub>6</sub> for use in GIS. One such alternative that is widely accepted as the best possible replacement for SF<sub>6</sub> is to use SF<sub>6</sub>-N<sub>2</sub> gas mixtures (at different percentages of SF<sub>6</sub>) as the insulating medium in GIS.

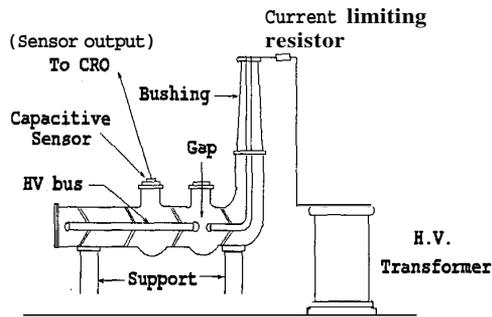
SF<sub>6</sub>-N<sub>2</sub> mixtures are the most thoroughly investigated among all known gas mixtures. Based on the research conducted worldwide, the optimum composition of SF<sub>6</sub>-N<sub>2</sub> mixture for practical applications is considered to be 40%SF<sub>6</sub> - 60%N<sub>2</sub> mixture [4]. But, recent studies carried out also suggest that SF<sub>6</sub>-N<sub>2</sub> mixture with SF<sub>6</sub> concentration as low as 20% can be used with an advantage [5]. Even with low SF<sub>6</sub> content, this mixture has been found to exhibit many of the desirable properties of pure SF<sub>6</sub> when used as an insulant.

Substantial amount of work has been done and reported with respect to the experimental and theoretical measurements of VFTO in pure SF<sub>6</sub> [1,2,6]. It has been reported in most of the results that the peak magnitude of the VFTO seldom crossed 2.0 p.u. [1,2], but there were occurrences of transients as high as 2.4-3.0 p.u. [2] in some other cases also. The breakdown time of the gap is normally between 4ns to 20ns [1,2] depending on the field inhomogeneity and the peak of the VFTO can occur about 200ns after the gap has broken down [1]. Although some work has been reported on measuring the breakdown strength of SF<sub>6</sub>-N<sub>2</sub> mixtures under uniform and non-uniform electric field gaps stressed by very fast transients, there is no published literature till date regarding the generation and characteristics of VFTO in an SF<sub>6</sub>-N<sub>2</sub> medium.

In the present study, experimental measurements of VFTO peak magnitudes and temporal characteristics have been carried out in SF<sub>6</sub>, N<sub>2</sub> and SF<sub>6</sub>-N<sub>2</sub> mixtures (at lower percentages of SF<sub>6</sub>).

## EXPERIMENTAL TECHNIQUE

Experiments for measurements of VFTO were carried out using a 145kV model GIS bus duct of Siemens, Germany make. The VFTO waveforms were recorded on a Digital Storage Oscilloscope with the help of a capacitive sensor developed specifically for this purpose. The experimental set up is shown in figure 1.



**Figure 1: Full experimental setup.**

### Test Gap and Procedure

Disconnecter operation for the generation of VFTO was simulated by the breakdown of a hemispherical gap, which is in-built into the bus duct model. The gap with an electrode diameter of 5cm was kept undisturbed at a spacing of 0.2mm throughout the current set of experiments. The GIS bus duct is a single floating bus of 2.45 meters length from the gap axis. Experiments for the measurement of VFTO were carried out at pressures ranging from 1 to 5 bars for all the cases. The high voltage bus was excited with a sinusoidal voltage of 50Hz from a 150kV high voltage test transformer. The bus duct was initially evacuated to very low pressures of around  $10^{-5}$  bars to remove air, moisture and other contaminants, which might be present inside. The duct is then filled with the appropriate gas in which experiment has to be performed. In the case of pure SF<sub>6</sub> and pure N<sub>2</sub>, the gas was filled directly and kept for about an hour before experiments were carried out. For SF<sub>6</sub>-N<sub>2</sub> mixtures, the duct was filled according to the partial pressure of the gases by which the gas having the lesser percentage in the mixture, i.e. SF<sub>6</sub> in the present case is let in first followed by the gas with higher content i.e. N<sub>2</sub>. The mixture was kept for 5-7 hours for proper mixing of the gases. Between successive breakdowns, a time delay of approximately 10 minutes was provided. The handling of SF<sub>6</sub>, i.e. evacuation, pressurizing and recycling etc. was done with the help of a gas recycling and pressurizing plant. The gases used were of ultra high purity grade.

### Measuring System

The fast transients were measured using a capacitive voltage sensor, which was developed in-house specifically for this purpose. The voltage rise time of the sensor is sufficiently steep for measuring the voltage rise of a disconnecter induced fast transient. The VFTOs were recorded on a 200MHz Tektronix Digital Storage Oscilloscope having a sampling rate of 1Gs/sample/sec. The VFTO measurements were carried out at an appropriate time sweep taking into consideration the accuracy with which the various parameters of the waveform can be measured.

## EXPERIMENTAL RESULTS

Typical VFTO characteristics recorded at a pressure of 5 bar for pure SF<sub>6</sub>, pure N<sub>2</sub> and SF<sub>6</sub>-N<sub>2</sub> mixtures with 5%, 10%, 15% and 20% SF<sub>6</sub> content in N<sub>2</sub> are shown in figure 2. Figure 3 shows the variations of the overvoltage factor with pressure for all the cases. The same data are shown in figure 4 as a function of %SF<sub>6</sub> content in N<sub>2</sub>. A comparison of the VFTO levels of mixtures containing 5%, 10%, 15% and 20% SF<sub>6</sub> concentration with those of pure SF<sub>6</sub> at pressures of 4 and 5 bars is shown in table 1.

The time to breakdown of the gap has been observed to be in the range of 5-5.5ns in pure SF<sub>6</sub> and mixtures (at all pressures) whereas it is 6.0ns in the case of N<sub>2</sub> till 4 bar and decreases to 5.5ns at 5 bar. The maximum peak of the VFTO is seen to occur around 18ns after the gap has broken down.

## OBSERVATIONS AND DISCUSSIONS

From figure 2, it can be seen that the nature of the VFTO waveforms is similar to the ones obtained earlier and available in literature. They have a very steep rising portion (4-10ns), a peak that doesn't occur in the steepest portion of the waveform and an oscillating tail, which settles down after around 400-500ns. All the VFTO waveforms in figure 2 are similar. The nature of the waveform depends upon the GIS system layout. In the present study, all the experiments were carried out using a single GIS bus duct, which was left unaltered after setting the gap and so there can be no change in the nature of the waveforms for different cases.

It can be seen from figure 3 that the overvoltage factor increases with increase in gas pressure in all the cases. In N<sub>2</sub>, the increase in overvoltage factor with gas pressure is very less whereas for pure SF<sub>6</sub>, it is almost linear. The trends for the mixtures with lower SF<sub>6</sub> content is in between the trends of N<sub>2</sub> and SF<sub>6</sub> and the overvoltage factor increases with gas pressure although the increase is not similar to that of SF<sub>6</sub>. The overvoltage factor depends on the breakdown voltage of the gap. Since the breakdown voltage of the gap increases with increase in gas pressure, the overvoltage factor also increases. It is also seen that the overvoltage factor in N<sub>2</sub> is lowest at all pressures compared to those in mixtures as well as pure SF<sub>6</sub>. This is because the breakdown voltage for N<sub>2</sub> is much lower than SF<sub>6</sub> and SF<sub>6</sub> containing mixtures.

From the graph in figure 4, it can be seen that the overvoltage factors increase when SF<sub>6</sub> concentration is increased in the mixture. It has been already mentioned that the overvoltage factor is a function of the breakdown voltage. With increase in the percentage of SF<sub>6</sub> in the mixture, the critical E/p (at which the rate of ionization ( $\alpha/p$ ) equals the rate of attachment ( $\eta/p$ ), or  $\alpha/p = \eta/p$ ) also increases. Thus there is an increase in the breakdown voltage and hence the overvoltage factor

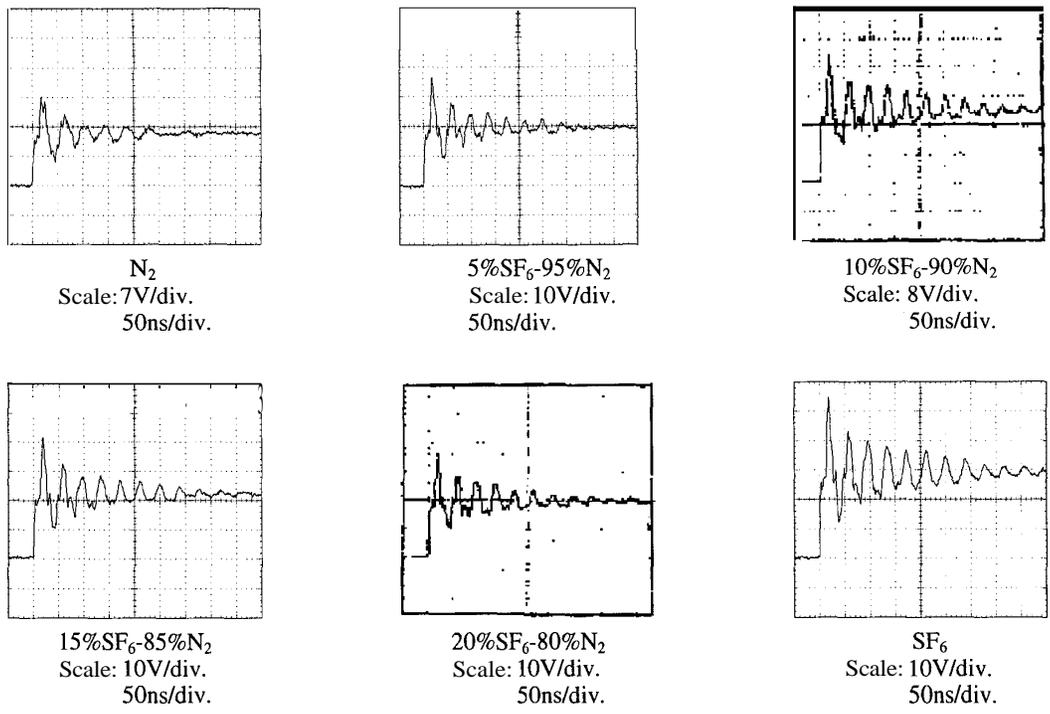
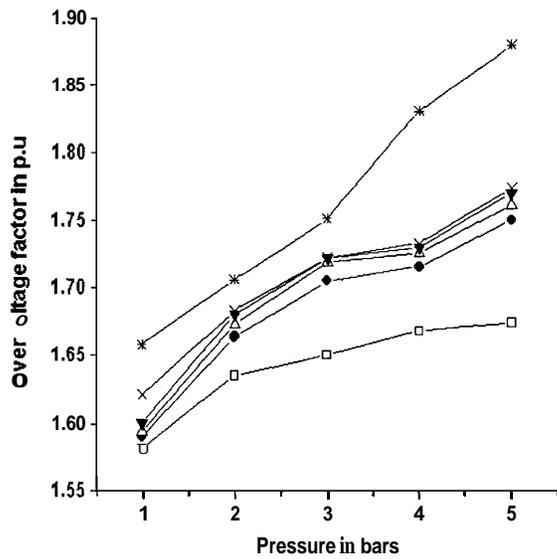
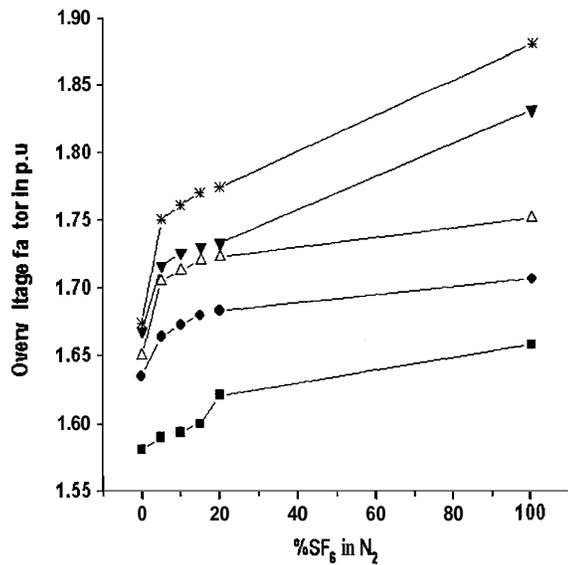


Figure 2: Characteristics of VFTOs in SF<sub>6</sub>-N<sub>2</sub> gas mixtures at 5 bars.



□: N<sub>2</sub>    ●: 5% SF<sub>6</sub>    Δ: 10% SF<sub>6</sub>  
 ▼: 15% SF<sub>6</sub>    ×: 20% SF<sub>6</sub>    \*: SF<sub>6</sub>

Figure 3: Pressure vs Overvoltage factor characteristics.



■: 1 bar    ●: 2 bar    Δ: 3 bar  
 ▼: 4 bar    \*: 5 bar

Figure 4: %SF<sub>6</sub> in N<sub>2</sub> vs Overvoltage factor characteristics.

**TABLE 1 - Maximum peak VFTO magnitudes at different mixture ratios at 4 and 5 bars**

Pressure (bars)	PEAK VFTO MAGNITUDE (in p.u.)					
	N <sub>2</sub>	5%SF <sub>6</sub> -95%N <sub>2</sub>	10%SF <sub>6</sub> -90%N <sub>2</sub>	15%SF <sub>6</sub> -85%N <sub>2</sub>	20%SF <sub>6</sub> -80%N <sub>2</sub>	SF <sub>6</sub>
4	1.668	1.716	1.726	1.730	1.733	1.831
5	1.674	1.750	1.761	1.770	1.774	1.881

increases with the concentration of SF<sub>6</sub> in the mixture. It is also observed that there is a steep increase in the overvoltage factor on addition of 5%SF<sub>6</sub> in the mixture. This observation is similar to the rapid increase in the breakdown voltage when 5%SF<sub>6</sub> is added to N<sub>2</sub>. When the SF<sub>6</sub> content was further increased in the mixture, the increase in the overvoltage factor becomes more pronounced, especially at 4 and 5 bars where the trend is almost a straight line. At lower pressures, the increase in the overvoltage factor is not too significant.

The variations in the VFTO magnitudes in gas mixtures studied are similar (but ill defined) to the non-uniform field breakdown due to corona stabilization observed earlier [7]. It can be observed from figure 3 that the difference in the overvoltage factors between mixtures containing 10%, 15% and 20% SF<sub>6</sub> in N<sub>2</sub> are not significant between pressures of 2 to 4 bars. In the present study, experiments were carried out with hemispherical electrodes at a gap spacing of 0.2mm. Hence, the field can be expected to be uniform. But on closer inspection of the electrodes, small amount of surface roughness was seen near the tip. These small surface irregularities become more prominent when very small gaps are used for experiments and thus the occurrence of corona stabilized breakdown of the gap cannot be ruled out. As the gap in the present study is very small, corona stabilization can be the reason behind such an observation. It can be emphasized here that similar observation is not seen in the case of N<sub>2</sub>.

The time to breakdown in all the cases under study has been found to be constant at around 5-5.5ns. Only in N<sub>2</sub>, the time to breakdown is 6.0ns till 4 bar and reduces to 5.5ns at 5 bar. These observations agree with the facts proposed by Pfeiffer [8] that for approximately uniform field gaps and small gap separations (similar to the present case of 0.2mm), the difference in the time lags between SF<sub>6</sub> and N<sub>2</sub> doesn't seem to be very important. This is found to be true between SF<sub>6</sub> and SF<sub>6</sub>-N<sub>2</sub> mixtures also. The time lags are slightly lower in SF<sub>6</sub> compared to N<sub>2</sub>, but this difference doesn't seem to have much practical importance. The formative time lags in all the cases under the experimental conditions

of the present study are almost the same and therefore do not play any important role in the discharge growth.

It is also observed from figure 2 that the maximum of the VFTO peaks occurs after a certain time, which is around 18ns in almost all the cases. The occurrence of the maximum peak of the VFTO at almost the same time in all the cases can be explained as follows. The GIS bus duct used for this experiment is a single floating bus of length 2.45 meters from the test gap. The time of travel (t) for the first reflection of the voltage wave generated from the test gap will be:

$$t = (2l) / v$$

where, l = length of the bus.

v = velocity of propagation of the voltage wave.

In the present case, a velocity of propagation 0.95 times the speed of light is assumed due to the presence of spacers. Then, the time of travel of the voltage wave is approximately 17.2ns, which is close to 18ns obtained from experiments under all practical conditions. Since the length of the bus is a constant and there are no impedance mismatches in the path of the travelling voltage wave, the peak of the VFTO occurs at the first reflection from the end of the bus.

## CONCLUSIONS

In the present study, the VFTO characteristics for SF<sub>6</sub>, N<sub>2</sub> and mixtures of SF<sub>6</sub> and N<sub>2</sub> at lower percentages of SF<sub>6</sub> were recorded and the VFTO magnitudes measured. Results show that the VFTO magnitudes in SF<sub>6</sub>-N<sub>2</sub> gas mixtures increase with increase in gas pressure as well as with increase in the %SF<sub>6</sub> content in the mixture. The magnitudes of VFTO were found to increase rapidly on addition of 5%SF<sub>6</sub> in N<sub>2</sub>. Also, the influence of corona stabilization was seen on the VFTO levels. The VFTO magnitudes are thus dependent on the breakdown process of the gap. No observation of any significant change in the time to breakdown of the gap could be made in all the cases.

Table 1 lists the peak VFTO magnitudes for pure SF<sub>6</sub> and its mixtures at 4 and 5 bars. It can be seen that the percentage decrease in the case of mixtures with 5% and 10% SF<sub>6</sub> content at 5 bar is quite significant compared to pure SF<sub>6</sub>. Thus taking into consideration the overvoltage factor in mind, the use of SF<sub>6</sub>-N<sub>2</sub> mixtures with lower SF<sub>6</sub> concentration in a GIS can be seriously thought of. However, a compromise has to be made on the working pressure and GIS design. Besides, the maintenance of a uniform mixture ratio at low percentages of SF<sub>6</sub> as well as the removal and recycling of the gas will be a major problem.

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