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# Characteristics of VFTO Generated in a GIS with $SF_6$-$N_2$ Gas Mixture as the Insulating Medium

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***Abstract:*** **This paper deals with the experimental characteristics of VFTO in pure $N_2$, pure $SF_6$ and $SF_6$-$N_2$ mixtures. The investigations are performed using a laboratory model bus duct. A capacitive type voltage sensor was used to measure the VFTO peak magnitudes and temporal characteristics. Measurements were carried out in $N_2$, $SF_6$ and $SF_6$-$N_2$ mixtures wherein the $SF_6$ concentration was varied from 10% to 40% over a pressure range of 1 bar to 5 bars. The results from the VFTO characteristics obtained for $SF_6$ and $SF_6$-$N_2$ mixtures show similar trends in variations. The levels of surge peak magnitudes are less than 2 p.u. for all the cases considered in the experimental pressure range. In $N_2$, the peak magnitude remains almost constant with increasing pressure but for pure $SF_6$, it increases almost linearly with pressure. On the other hand, for the gas mixtures, the difference in peak magnitudes is not significant at pressures between 2 to 4 bars. The occurrence of corona stabilization during breakdown of the gap is thought to be the cause for this behavior.**

## INTRODUCTION

Steep fronted transients are generated in GIS during operation of disconnector switches [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].

Substantial amount of work has been done and reported with respect to the experimental and theoretical measurements of VFTO in pure $SF_6$ [4]. It has been reported in most of the published experimental results that the peak magnitude of the VFTO seldom crossed 2.0 p.u. [1,2], but there were occurrence of transients as high as 2.4-3.0 p.u. [2] in some other cases. 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].

$SF_6$ is the main insulating medium in almost all gas insulated high voltage equipments. However, in recent years, due to the many problems associated with the use of $SF_6$, like it being a greenhouse gas, formation of toxic and corrosive compounds when subjected to an electrical discharge and the difficulty in removing it from the atmosphere, investigations are in progress to evolve substitutes to minimize the use of $SF_6$. One such alternative is to use other gases or gas mixtures containing $SF_6$ instead of pure $SF_6$.

$SF_6$-$N_2$ mixtures are the most thoroughly investigated among all known gas mixtures. Based on the research conducted worldwide, the optimum composition of $SF_6$-$N_2$ mixture for practical applications is considered to be 40%$SF_6$ - 60%$N_2$ mixture [5]. Recent studies carried out also suggest that $SF_6$ mixture with $SF_6$ concentration as low as 20% can be used with an advantage. Even with low $SF_6$ content, this mixture exhibits many of the desirable properties of pure $SF_6$ when used as an insulant. Although some work has been reported on measuring the breakdown strength of $SF_6$-$N_2$ mixtures under uniform and non-uniform electric field gaps stressed by very fast transients, there is no published literature regarding the generation and characteristics of VFTO in an $SF_6$-$N_2$ medium.

In the present study, experimental measurements of VFTO peak magnitudes and temporal characteristics have been carried out in pure $SF_6$, pure $N_2$ and $SF_6$-$N_2$ mixtures using a laboratory model GIS bus duct.

## EXPERIMENTAL SETUP

The experiments for the measurement of VFTO were carried out using a 145kV Gas Insulated Bus Duct of Siemens, Germany make. The whole experimental setup is shown in figure 1.

### Test Gap and Procedure

Disconnector operation for the generation of VFTO was simulated by the breakdown of a hemispherical gap, which is in-built in the bus duct model. The gap with a hemispherical diameter of 5cm can be varied from zero to a few centimeters. The GIS bus duct is a single floating bus of 2.45 meters length from the gap. Experiments for the measurement of VFTO were carried out at pressures from 1 to 5 bars. The high voltage bus was excited with a sinusoidal voltage of 50Hz from a 150kV, 50kVA high voltage 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 case of pure $SF_6$ and pure $N_2$, the gas was filled directly and kept for sometime before experiments were carried out. For $SF_6$-$N_2$ mixtures, the duct was filled according to the partial pressure of the gases by putting in the gas having the lesser percentage in the mixture, i.e. $SF_6$ in the present case, first and $N_2$ later on. The mixture was kept for 5-7 hours for proper mixing of the gases. A time delay of approximately 10 minutes was provided between each breakdown. The handling of $SF_6$, 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.

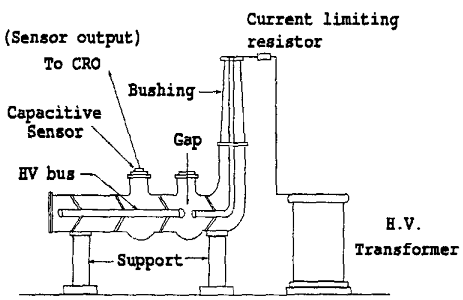



Fig.1 - Full experimental setup.

## Measuring System

The VFTO measurements were carried out using a capacitive voltage sensor specifically developed in-house for this purpose. The Very Fast Transients generated are recorded on an oscilloscope, which is connected from the output of the sensor through a 0.6m long cable. The oscilloscope used was a 200 MHz TEKTRONIX Digital Storage Oscilloscope having a sampling rate of 1Gsample/sec. The VFTO measurements are done at an appropriate time sweep taking into consideration the accuracy with which the VFTO magnitudes and rise times can be measured.

## EXPERIMENTAL RESULTS

Typical VFTO characteristics at a pressure of 5 bar for pure $N_2$, pure $SF_6$ and mixtures of $SF_6$ and $N_2$ with 10%, 20% and 40% $SF_6$ are shown in figure 2. Figure 3 shows the variations of VFTO magnitude with gas pressure. The same data are shown in figure 4 as a function of $SF_6$ concentration in $N_2$. A comparison of the VFTO peak magnitudes of pure $SF_6$ with 10%, 20% and 40% $SF_6$ in $N_2$ mixtures at 5 bar is shown in table 1.

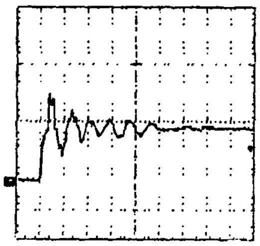
The sparking time of the gap as seen from the VFTO waveforms obtained is almost constant at 5.0 - 5.5ns in pure $SF_6$ and its mixtures at all pressures, while it is 6.0ns - 6.5ns in pure $N_2$. It is seen that the maximum peak of the VFTO occurs after a certain lapse of time, which is about 19ns in all the cases.

## DISCUSSION

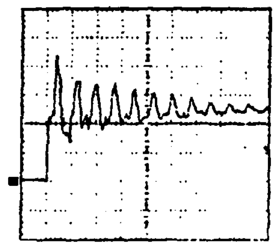
From the graph shown in figure 2, it is seen that the nature of the fast transient waveforms are as expected. It has a very steep rising portion, a peak that doesn't occur in the steepest portion of the wave and an oscillating part, which settles down after some time.

It can be seen from figure 3 that the VFTO magnitudes in all the cases increase with the gradual increase of pressure and it is almost a straight line in the case of pure $SF_6$. The VFTO magnitudes in $N_2$ are very low compared to pure $SF_6$ at all pressures. The VFTO magnitudes in the case of mixtures are also found to be as expected and they increase with the increase in pressure as well as with the increase in the percentage of $SF_6$ in the mixture. This is due to the fact that the critical E/p (at which the rate of ionization ($\alpha/p$) equals the rate of attachment ($\eta/p$), or $\alpha/p = \eta/p$) increases with the increase in concentration of $SF_6$ in $N_2$. The magnitudes are somewhat lower at lower pressures compared to $SF_6$, but increase at higher pressures. The VFTO magnitudes for the pure gases and gas mixtures entirely depend on the breakdown voltage of the gap and trends in the variations of the breakdown characteristics are reflected on the VFTO characteristics also.

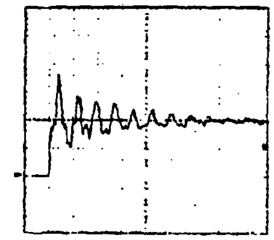
The variations in VFTO magnitudes in the gas mixtures studied and also in pure $SF_6$ are similar (but ill defined) to the non-uniform field breakdown due to corona stabilization observed earlier [5]. The VFTO magnitude increases very rapidly when $SF_6$ concentration in $N_2$ increases from 0% to 10% (figure 4) as the increase in breakdown voltage of the mixture is also quite significant compared to the breakdown voltage of pure $N_2$. But, it is interesting to note that there is negligible difference in the VFTO magnitudes for mixtures containing 10% and 20% $SF_6$ and also between 40% and 100% $SF_6$ at pressures between 2 and 4 bars (figure 3). In the present study, experiments were carried out using hemispherical electrodes having a gap distance of 0.2mm. Hence, the field can be expected to be uniform. But, on closer inspection of the electrodes, surface erosion over a small area near the tip of the electrodes was observed. These small surface irregularities become more prominent when very small gaps are used for experiments and thus the occurrence of corona



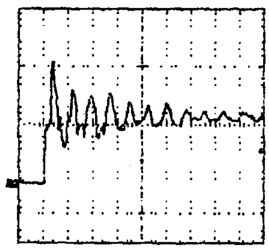
(a) **100%$N_2$**



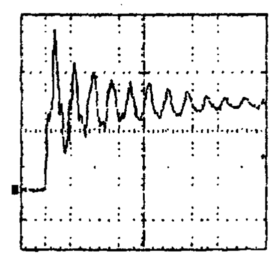
(b) **10%$SF_6$ - 90%$N_2$**



(c) **20%$SF_6$ - 80%$N_2$**



(d) **40%$SF_6$ - 60%$N_2$**



(e) **100%$SF_6$**

Figure 2 - VFTO Characteristics of the gases and gas mixtures at 5 bars.

Volts/division: fig.2(a) - 7 V/div. ; fig.2(b) - 8 V/div. ; fig.2(c) - 10 V/div. ; fig.2(d) - 10 V/div. ; fig.2(e) - 10V/div.
Time Scale : 50ns / division for all the figures

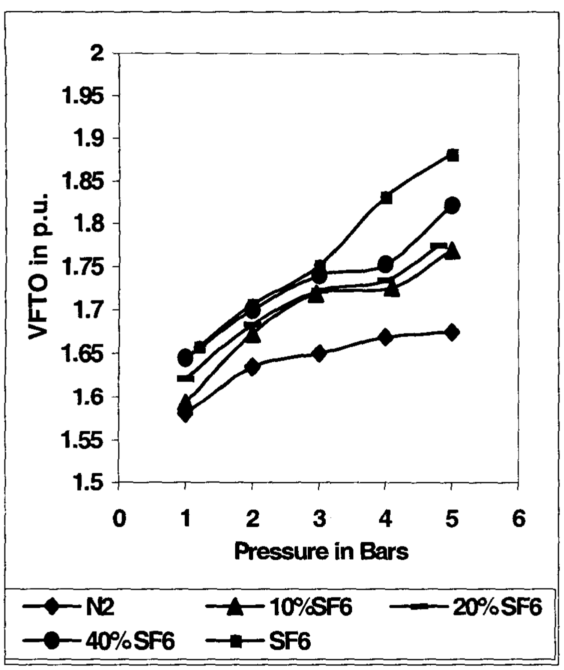



Figure 3: VFTO Magnitude vs Pressure characteristics

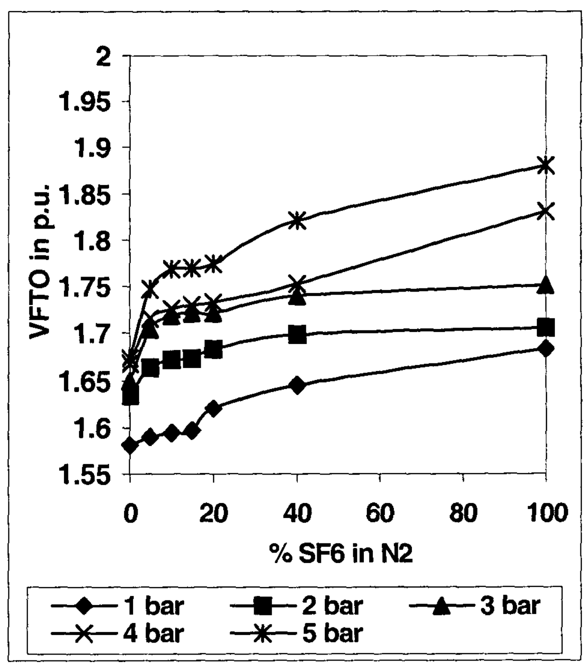



Figure 4: VFTO magnitude vs %$SF_6$ in $N_2$ characteristics

**Table 1 - Maximum peak VFTO magnitudes at different mixture ratios at 5 bars.**

| Sl. No. | Peak VFTO for pure $N_2$ | Peak VFTO for 10% $SF_6$-90% $N_2$ | Peak VFTO for 20% $SF_6$-80% $N_2$ | Peak VFTO for 40% $SF_6$-60% $N_2$ | Peak VFTO for pure $SF_6$ |
|---|---|---|---|---|---|
| 1. | 1.674 | 1.7689 | 1.7740 | 1.8215 | 1.8812 |

stabilized breakdown of the gap cannot be ruled out. As the gap used is very small, corona stabilization effect can be the reason behind such an observation. It may be emphasized here that similar observation is not seen in the case of pure $N_2$.

Figure 2 clearly shows that all the characteristics look similar. The similarity in the waveforms is because of the simple design of the bus duct. It can be also seen that the time to breakdown of the gap remains almost constant at 5.0 - 5.5ns for pure $SF_6$ and its mixtures. In the case of pure $N_2$, the breakdown time of the gap is 6.0 - 6.5ns at all pressures. These observations are in agreement with the observation made by W. Pfeiffer [6] that for approximately uniform fields and small gap separations, the difference in the characteristics of time lags (formative time) between $N_2$ and $SF_6$ does not seem to be very important. This fact is found to be true for the case of mixtures also as can be seen from the characteristics. The formative time lags in $SF_6$ are slightly lower compared to $N_2$, but this difference appears to have no 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 occur after a certain time, which is around 19ns in almost all the cases. The stabilization of the peak VFTO rise time in all the cases can be explained as follows. The GIS bus duct used for this experiment is a single floating bus with a length of 2.45 meters from the test gap. The time of travel for the first reflection for a 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 19ns obtained from the experiments, in all practical conditions. Since the length of the bus is constant and there are no impedances in the path of the travelling voltage wave, the peak of the voltage wave occurs at the first reflection from the end of the bus.

# CONCLUSIONS

In the present study, the VFTO characteristics for $SF_6$, $N_2$ and mixtures of $SF_6$-$N_2$ at different percentages of $SF_6$ were recorded and the VFTO magnitudes measured. The results show that the VFTO magnitudes in $SF_6$-$N_2$ gas mixtures increase with increase in gas pressure. The magnitudes of VFTO were found to increase rapidly on addition of 10%$SF_6$ in $N_2$. No significant change in the time to breakdown of the gap and the time to maximum peak occurrence of the VFTO was observed in all the cases.

Table 1 lists the peak VFTO magnitudes for pure $SF_6$ and its mixtures at a pressure of 5 bar. It can be seen that the percentage decrease in the case of 10%$SF_6$ in $N_2$ mixture at 5 bar is quite significant compared to pure $SF_6$. This will be more at higher pressures. Thus, considering the fact that the breakdown strength of 10%$SF_6$ in $N_2$ mixture will be more at higher pressures, its use in GIS can be seriously thought of. However, problems regarding the maintenance of a uniform mixture ratio at low percentages of $SF_6$ as well as the removal and recycling of the gas mixture will pose the biggest problem.

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