# Toepler's Spark Law in a GIS with Compressed $SF_6$-$N_2$ Mixture

Santanu Singha and M. Joy Thomas
Department of High Voltage Engineering
Indian Institute of Science
Bangalore, 560 012 India

## ABSTRACT

**This paper deals with the experimental measurements and analysis of the formative time lags to breakdown and an estimation of the Toepler's constant for gas gaps, under the application of 50 Hz ac voltage. The experiments were carried out in a 145 kV gas insulated system (GIS) bus duct with pure $N_2$, pure $SF_6$ and $SF_6$-$N_2$ mixture as insulating media. The formative time lags to breakdown in the gas gaps were measured using a fast response capacitive sensor. Toepler's spark law has been used to explain the breakdown phenomenon in the GIS and the values of Toepler's constant ($k_t$), which gives an estimation of the formative time lags, were determined. Results show that the formative time lags vary inversely with gas pressure and the gas mixture concentrations for two gaps studied (0.46 mm and 0.61 mm). In the case of another gap (0.20 mm), the variation in the formative time lags with pressure as well as $SF_6$ concentration in the mixture has been found to be negligibly small between gas mixtures, although significant variation can be seen between pure $SF_6$ and pure $N_2$. Toepler's constant, $k_t$, increases with gas pressure as well as $SF_6$ concentration in the mixture for the gaps studied. Hence, $k_t$ is a function of the gas pressure and the concentrations of $SF_6$ in the gas mixture for the above-mentioned gaps.**

Index Terms — **Gas insulated systems, very fast transient over voltage, Toepler's spark law, formative time lags, $SF_6$-$N_2$ mixtures.**

## 1 INTRODUCTION

GAS insulated systems (GIS) have become a major component of the power network worldwide and they have been used with considerable success over the past 30 years [1]. Despite their excellent performance over so many years, GIS have their own problems also. One of the important issues of concern is the generation of very fast transient over voltages (VFTO) in GIS during switching operations, especially at operational voltage levels of 420 kV and beyond [2]. There are mainly two major sources of origin of the VFTOs in a GIS: switching of disconnectors/circuit breakers and earth faults. In both cases, there is an instantaneous voltage collapse during occurrence of breakdown either between the contacts of the disconnector/breaker or between phase and ground, which leads to the generation of steep voltage surges with very short rise times. In order to understand the complete phenomena behind the occurrence of these fast transients, it becomes extremely important to know the total time required for the plasma channel to bridge the gap during breakdown, since this time determines the characteristics of the VFTO.

With escalating power requirements worldwide, the components, which are interconnected in the GIS are also increasing day by day, thus making the GIS network more and more complex. It then becomes extremely difficult and tedious to measure these fast transient voltages through actual experiments conducted in the GIS. In such a case, VFTO characteristics can be analyzed using computer simulation methods, mainly the EMTP, and the basic relation, which has been successfully used for disconnector/circuit breaker arc simulations, is the Toepler's spark law [2]. To successfully model and simulate the GIS for attaining different characteristics of the VFTO using Toepler's relation, a major requirement is the understanding of the formative time lags and the range of Toepler's constant under different experimental parameters.

Another issue of concern in recent years is related to the continuous use of $SF_6$ in GIS in spite of the fact that

*Manuscript received 1 July 2001, in final form 11 December 2002.*

$SF_6$ has been identified as a potent greenhouse gas (with the added difficulty of removing it from the atmosphere) contributing to the global warming of the environment. A possible solution to this problem is to replace $SF_6$ with a gaseous mixture of $SF_6$ and $N_2$, as this mixture has been widely accepted as the best possible replacement to $SF_6$ for use as the insulating medium in GIS [1].

Based on the present scenario, it is quite possible that $SF_6$-$N_2$ gas mixture might replace pure $SF_6$ in GIS in the near future. To allow confident and successful use of this gas mixture in GIS, it is necessary to analyze the VFTO characteristics in a GIS with $SF_6$-$N_2$ gas mixture insulation and thus data on the formative time lags to breakdown and the range of Toepler's constant has to be known. In this regard, the present work undertakes an experimental investigation of the breakdown of a gap in a GIS under 50 Hz ac voltage with $SF_6$-$N_2$ gas mixture as the insulating medium. The formative time lags to breakdown were experimentally determined and the values of Toepler's constant were calculated using Toepler's spark law at different gas/gas mixture pressures and different gas mixture concentrations.

## 2 FORMATIVE TIME LAGS TO BREAKDOWN IN A GAS GAP

In the present context, the formative time lags to breakdown of a gas gap ($t_f$) is defined as the time taken for the voltage to drop from 90% to 10% of its value during occurrence of breakdown. This time corresponds to the interval when a conducting plasma channel bridges the inter-electrode gap equalizing the potential at both the electrodes. This conducting plasma channel is formed in a very short time, which is of the order of a few nanoseconds. During this time, the spark resistance changes from a very high value ($\gg 10^6\ \Omega$) to a very low value ($\cong 5\ \Omega$) [3, 4]. This time dependent arc resistance of the conducting channel is the main criterion that is considered while estimating the formative time to breakdown of the gas gap. In general, the arc resistance appears to be inversely proportional to some function of the arc current [5]. Many relations obtained by theoretical or experimental methods are cited in literature to calculate the instantaneous value of the spark channel resistance [5]. But, it has been found that only two relations, namely, the relation obtained by Weizal and Rompe and the Toepler's empirical relation agree with experimental data over short time intervals (order of nanoseconds) [6].

The experimental gap range used by Toepler [5] is very much close to the gaps considered in the present study as compared to the inter-electrode gaps used by various earlier researchers [5, 7]. Taking this fact into account and also because of its proven relevance with respect to VFTO phenomena in GIS, Toepler's relation is used to explain the breakdown behavior in the present investigations.

According to Toepler, the instantaneous value of the spark resistance $R_t$ is inversely proportional to the charge conducted through the spark channel [6].

$$R_t = l\frac{k_t}{\int_0^t i dt} \quad (1)$$

where $l$ is the length of the discharge gap in cm, $i$ the discharge current in A and $k_t$ the Toepler's constant in Vs/cm.

If the spark is due to a discharge of an ideal capacitor, the instantaneous voltage during breakdown, $U$ is [4]

$$U = \frac{V}{1+\exp\left[Vk_t^{-1}t_f l^{-1}\right]} \quad (2)$$

where $V$ is the breakdown voltage in V and $t_f$, the formative time lag to breakdown in ns.

From equation (2) [4]

$$t_f = \frac{4.4\times 10^6 k_t l}{V} \quad (3)$$

The dependence of the formative time lags to breakdown on the gas pressure in the case of very small air gaps has been experimentally determined by Mesyats et. al. [7]. A similar study was undertaken by Vorob'ev et. al. [8] to study the effect of conductivity formation in the spark in various gases and concluded that the breakdown time of the gap is a function of the gas pressure in the case of air, $N_2$, $H_2$, $CO_2$, He and $CCl_2F_2$. Toepler obtained the first value of Toepler's constant ($1.5\times 10^{-4}$ Vs/cm) by fitting experimental results of arc resistance vs time [9]. Pfeiffer [10] obtained a Toepler's constant value of $0.5\times 10^{-2}$ Vs/m for air, $N_2$ and $SF_6$. Osmokrovic et. al. [4] carried out experiments to measure the formative time lags to breakdown in a few gases and gas mixtures and found out that the formative time lags as well as the Toepler's constant are functions of various GIS parameters like pressure, mixture concentration, gap distance, the field inhomogeneity of the inter-electrode gap etc., but at gaps in the range of 1 mm to 5 mm only and mainly under dc stress. However, to the authors' knowledge, formative time lags and values of Toepler's constant at very small gaps with $SF_6$-$N_2$ gas mixture insulation and under 50 Hz ac voltage are not available in literature.

## 3 EXPERIMENTAL SET-UP AND PROCEDURE

The experiments for measuring the formative time lags to breakdown were carried out in a 145 kV GIS bus duct shown in Figure 1 [11]. The GIS bus duct has an in-built and adjustable hemispherical electrode gap with 5 cm diameter electrodes. The busbar is open at one end and the open length of the busbar from the point of breakdown of

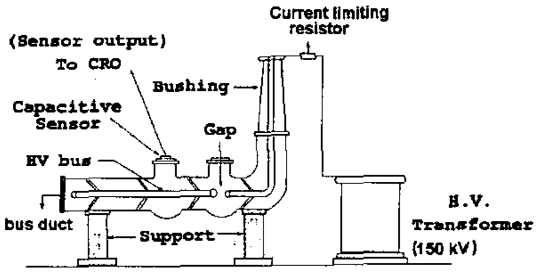

**Figure 1.** Experimental set-up for measurement of formative time lag.

the gap is 2.45 meters. Formative time lags to breakdown were measured at gap distances of 0.20 mm, 0.46 mm and 0.61 mm respectively in $SF_6$-$N_2$ gas mixture with concentrations of $SF_6$ varying from 0 to 100% in the pressure range 100–500 kPa. For accurate measurements and also to confirm the alignment of the electrode surfaces, the gap spacings were measured using a filler gauge to an accuracy better than $\pm 0.5\%$. Once the gap was adjusted, experiments in all gas mixture ratios and at different gas/gas mixture pressures were conducted without disturbing the gap again. The gas pressure in the GIS was measured with a pre-calibrated pressure gauge connected to the bus duct to an accuracy of up to $\pm 5\%$. The HV bus was excited with a sinusoidal voltage of 50 Hz from a 150 kV HV test transformer. Over the range of voltages in the present study, the transformer is assumed to be discharge free.

The bus duct was initially evacuated to a very low pressure of around $10^{-3}$ kPa to remove air, moisture and other contaminants present inside. The duct was then filled with the appropriate gas in which experiments were performed. In the case of pure $SF_6$ and pure $N_2$, the gas (99.9% purity) was filled directly and left for about 1 h before starting the experiments. For preparing $SF_6$-$N_2$ mixtures, the duct was filled according to the partial pressure of the gases. In this method, the gas having the lesser percentage content in the mixture, i.e., $SF_6$ in the present case is let in first followed by the gas with higher content in the mixture, i.e., $N_2$. Between successive breakdowns, a time delay of approximately 10 minutes was provided. The handling of $SF_6$ gas, i.e., evacuation, pressurizing and recycling etc., was done with the help of a gas recycling and pressurizing plant.

The formative time lags to breakdown were measured using a fast response capacitive sensor, which was designed and developed specifically for this purpose [12]. The voltage rise time of the sensor (the time to rise from 10% to 90% of the full amplitude) is sufficiently steep for measuring the voltage rise of a disconnector induced fast transient. This has been experimentally verified by a step response measurement and the rise time has been found to be approximately 2.1 ns [12]. The fast transients generated due to the breakdown of the gap are recorded on an oscilloscope (200 MHz Tektronix digital storage oscilloscope having a sampling rate of 1 Gs/s and 1.2 ns rise time). The values of the formative time lags to breakdown for each setting (i.e., for a given gap, gas mixture ratio and gas pressure) during the current investigations has been obtained by taking an average of 30 measurements. The experimental error in the measurements (from the capacitive sensor and the oscilloscope) has been taken into consideration while arriving at the final value of the formative time lag. The rate of increase of the applied voltage leading to the breakdown of the gap was maintained at a constant rate to ensure that the breakdown of the gap occurs at the peak of the ac voltage wave. The readings recorded at each of the settings were consistent in all the breakdowns, with occasional occurrences of minor variations, but those were limited to a maximum of $\pm 2\%$. A sample measurement with different parameters of interest is shown in Figure 2.

## 4 RESULTS AND DISCUSSIONS

Figure 2 shows the fast transient waveforms (measured using the capacitive sensor) generated during breakdown in the gas gap. It is quite clear that the formative time ($t_f$) can be measured from the fast transient waveform recorded at the lower time scale (5 ns/div). As soon as the breakdown of the gap occurs and the spark channel bridges the inter-electrode gap, a surge is generated (during the time period shown by points O and A in Figure 2) which shows the equalization of potential at the other electrode. This time gap between O and A thus gives the breakdown time (or formative time lag) of the gap. Since the busbar acts as a lossless transmission line, the voltage wave generated due to breakdown of the gap travels along the busbar and gets reflected from all the impedance mismatch points and finally from the open end of the bus. This reflected voltage wave gets superimposed on to the original voltage wave starting at point A and the final reflected wave from the open end of the bus reaches at point B as seen in Figure 2 (recorded at 5 ns/div). Consequently, the oscillations as seen in the fast transient waveform are due to the superimposition of these reflected travelling waves. The waveform recorded at 50 ns/div. shows the main frequency of the dominating VFTO component ($\approx 20$ MHz), which is determined by the total length of the experimental set-up. At all the gap spacings and at different gas or gas mixture pressures and different gas mixture ratios, the waveforms were recorded and the formative time lags to breakdown were measured in a similar way.

The formative time lags at the gap spacing of 0.20 mm are shown in Table 1 whereas data at the other two gaps are shown as variations with respect to the gas pressure and gas mixture concentration in Figures 3–6. Figures 3 and 4 show the variations of the formative time with gas pressure and concentrations of $SF_6$ in $N_2$, respectively for 0.46 mm gap. Similarly, for the gap spacing of 0.61 mm,

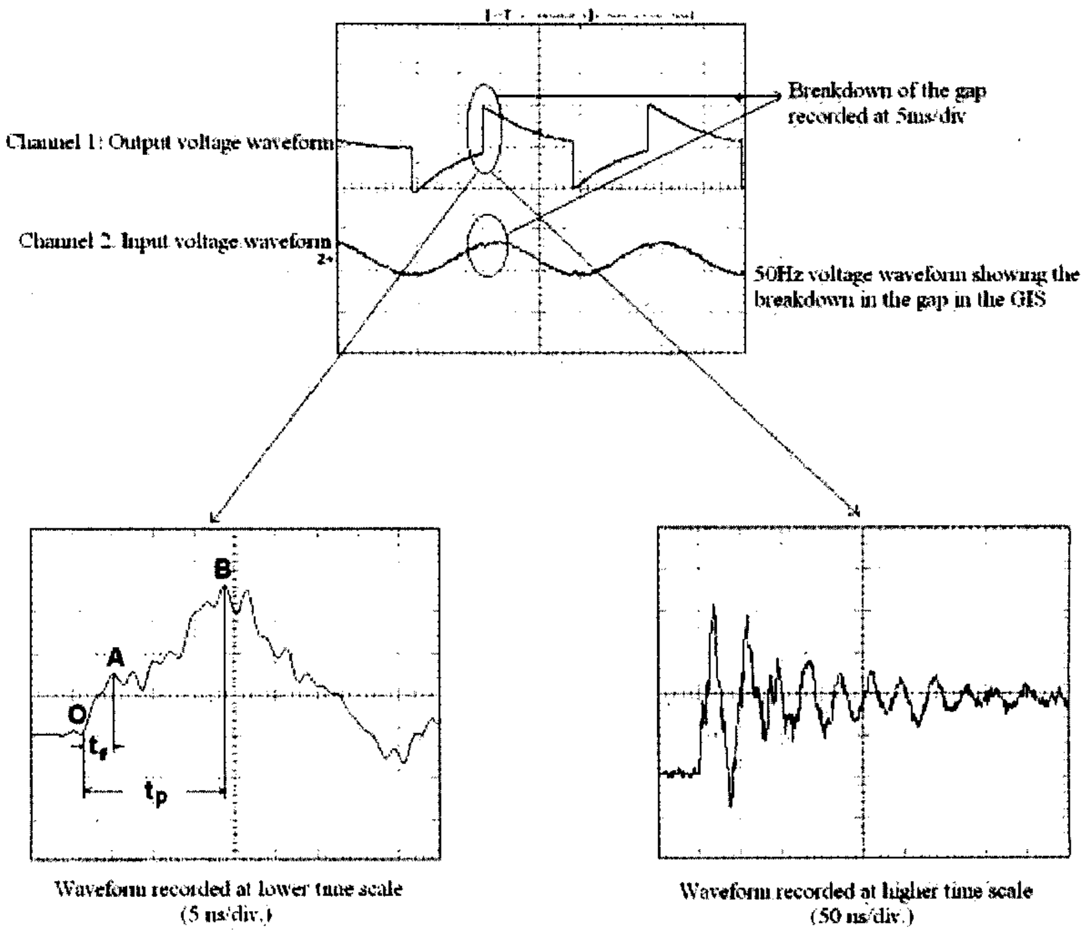


**Figure 2.** Fast transient waveform generation during gap breakdown. $t_f$, formative time (OA). Points O & A correspond to the 10% and 90% voltage drop across the gap; $t_p$, time to peak of very fast transient.

**Table 1.** Formative time lags (in ns) in gases/gas mixtures at a gap spacing of 0.2 mm and different gas pressures.

| Pressure (kPa) | Pure $SF_6$ | 40%$SF_6$-60%$N_2$ | 20%$SF_6$-80%$N_2$ | 15%$SF_6$-85%$N_2$ | 10%$SF_6$-90%$N_2$ | 5%$SF_6$-95%$N_2$ | Pure $N_2$ |
|---|---|---|---|---|---|---|---|
| 100 | 4.95 | 4.95 | 4.95 | 4.95 | 4.95 | 4.95 | 5.50 |
| 200 | 4.39 | 4.95 | 4.95 | 4.95 | 4.95 | 4.95 | 5.50 |
| 300 | 4.39 | 4.95 | 4.95 | 4.95 | 4.95 | 4.95 | 5.50 |
| 400 | 4.39 | 4.39 | 4.39 | 4.95 | 4.95 | 4.95 | 5.50 |
| 500 | 4.39 | 4.39 | 4.39 | 4.39 | 4.95 | 4.95 | 4.95 |

the variations of the formative times with gas pressure and $SF_6$ concentration are shown in Figures 5 and 6 respectively.

Using Toepler's Spark Law and the values of formative time lags and breakdown voltages obtained from the present experiments (Table 2), the values of Toepler's constant were also calculated for the gaps of 0.46 mm and 0.61 mm. The values of Toepler's constant were not calculated in the case of 0.20 mm gap since no significant variations in the formative time lags could be observed in gas mixtures with variations of the gas pressure and gas mixture concentration. For 0.46 mm gap, the variations of the Toepler's constant with respect to the gas pressure and

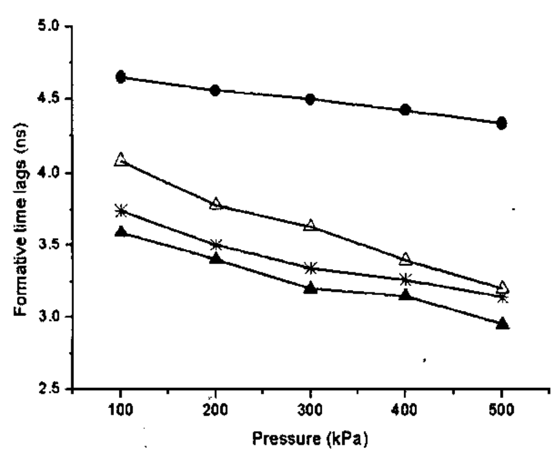


**Figure 3.** Pressure vs formative time lags at 0.46 mm gap. ▲ $SF_6$; ∗ 20% $SF_6$-80% $N_2$; △ 10% $SF_6$-90% $N_2$; ● $N_2$.

the concentration of $SF_6$ are shown in Figures 7 and 8, respectively. In the same way, Figures 9 and 10 show the variations of the Toepler's constant with the gas pressure and gas mixture ratio at the gap spacing of 0.61 mm.

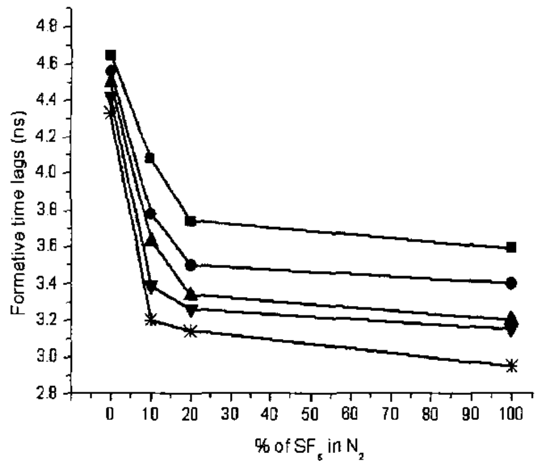


**Figure 4.** %$SF_6$ in $N_2$ vs formative time lags at 0.46 mm gap. ■ 100 kPa; ● 200 kPa; ▲ 300 kPa; ▼ 400 kPa; * 500 kPa.

**Table 2.** Breakdown voltages at different gas mixture concentrations and gas pressure in all gap spacings.

| | | Breakdown Voltage (kV) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Gap (mm) | Pressure (kPa) | Pure $SF_6$ | 40%$SF_6$ in $N_2$ | 20%$SF_6$ in $N_2$ | 15%$SF_6$ in $N_2$ | 10%$SF_6$ in $N_2$ | 5%$SF_6$ in $N_2$ | Pure $N_2$ |
| 0.20 | 100 | 2.3 | 1.85 | 1.28 | 1.24 | 1.093 | 1.035 | 0.633 |
| | 200 | 3.22 | 2.43 | 2.24 | 2.14 | 1.898 | 1.662 | 1.15 |
| | 300 | 5.3 | 3.47 | 3.2 | 3.1 | 2.956 | 2.82 | 2.3 |
| | 400 | 7.47 | 6.55 | 6.13 | 5.45 | 5.12 | 4.49 | 2.85 |
| | 500 | 9.27 | 8.86 | 7.96 | 7.06 | 6.53 | 5.44 | 3.24 |
| 0.46 | 100 | 3.54 | NA | 2.65 | NA | 2.07 | NA | 1.44 |
| | 200 | 6.9 | | 5.37 | | 4.84 | | 2.75 |
| | 300 | 10.98 | | 8.58 | | 6.81 | | 4.35 |
| | 400 | 15.61 | | 11.49 | | 9.84 | | 6.94 |
| | 500 | 18.88 | | 14.58 | | 12.7 | | 8.63 |
| 0.61 | 100 | 5.35 | 4.06 | 3.6 | NA | 2.86 | 2.097 | 1.8 |
| | 200 | 8.02 | 6.7 | 5.84 | | 5.22 | 4.94 | 3.6 |
| | 300 | 11.95 | 10.14 | 9.08 | | 7.68 | 7.35 | 5.3 |
| | 400 | 16.6 | 14.21 | 12.35 | | 10.45 | 10.01 | 7.2 |
| | 500 | 19.23 | 17.42 | 15.77 | | 14.18 | 13.03 | 9 |

NA: Not available.

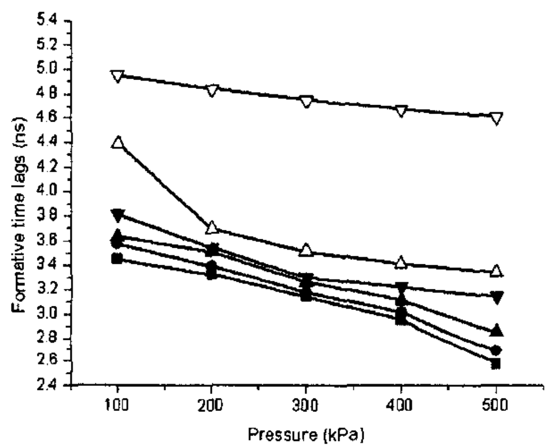


**Figure 5.** Pressure vs formative time lags at 0.61 mm gap. ■ $SF_6$; ● 40% $SF_6$-60% $N_2$; ▲ 20% $SF_6$-80 %$N_2$; ▼ 10% $SF_6$-90% $N_2$; △ 5% $SF_6$-95% $N_2$; ▽ $N_2$.

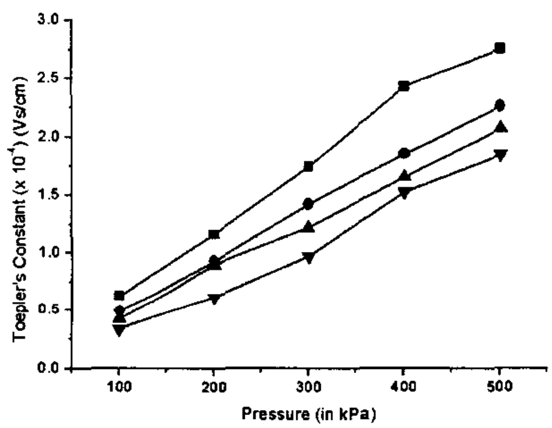


**Figure 7.** Pressure vs Toepler's constant at 0.46 mm gap. ▼ $N_2$; ▲ 10% $SF_6$-90% $N_2$; ● 20% $SF_6$-80% $N_2$; ■ $SF_6$.

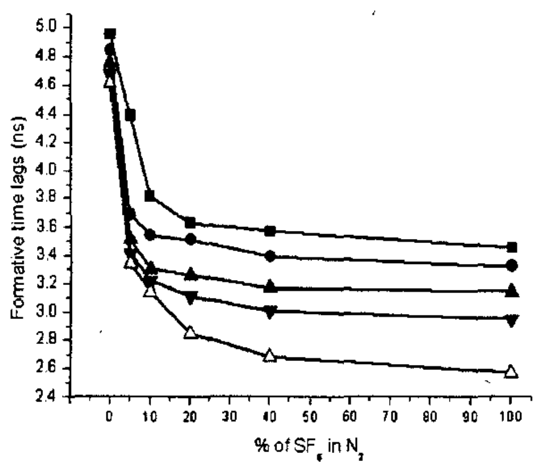


**Figure 6.** %$SF_6$ in $N_2$ vs formative time lags at 0.61 mm gap. ■ 100 kPa; ● 200 kPa; ▲ 300 kPa; ▼ 400 kPa; △ 500 kPa.

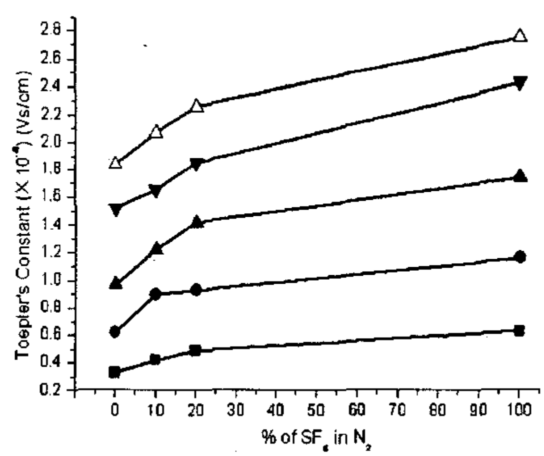


**Figure 8.** %$SF_6$ in $N_2$ vs Toepler's constant at 0.46 mm gap. ■ 100 kPa; ● 200 kPa; ▲ 300 kPa; ▼ 400 kPa; △ 500 kPa.

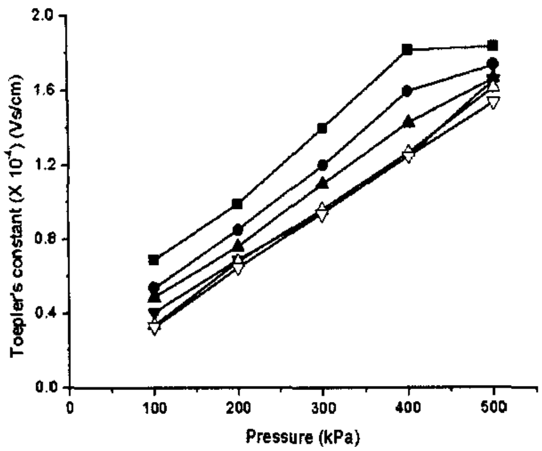


**Figure 9.** Pressure vs Toepler's constant at 0.61 mm gap. ▽ $N_2$; △ 5% $SF_6$-95% $N_2$; ▼ 10% $SF_6$-90% $N_2$; ▲ 20% $SF_6$-80% $N_2$; ● 40% $SF_6$-60% $N_2$; ■ $SF_6$.

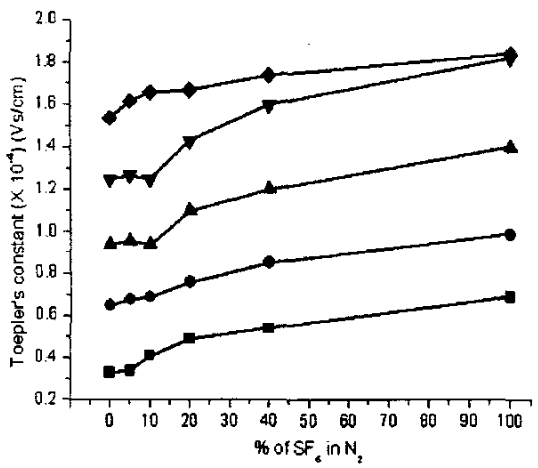


**Figure 10.** %$SF_6$ in $N_2$ vs Toepler's constant at 0.61 mm gap. ■ 100 kPa; ● 200 kPa; ▲ 300 kPa; ▼ 400 kPa; ◆ 500 kPa.

## 4.1 FORMATIVE TIME LAGS TO BREAKDOWN

It can be observed from Table 1 that the formative time to breakdown of 0.20 mm gap do not vary significantly (except for variations between pure $SF_6$ and pure $N_2$) irrespective of changes in the gas pressures at different gas mixture ratios. In pure $N_2$, the time to breakdown remains constant with increasing pressure except at 500 kPa where it is lower. In the case of pure $SF_6$, the formative time remains constant at 4.39 ns at all pressures except at 100 kPa and these lie in the time range specified earlier in literature [2, 3]. With regards to $SF_6$-$N_2$ mixtures, the formative time lags are constant at 4.95 ns at all pressures with 10% $SF_6$ in $N_2$, while at mixtures containing 20 and 40% $SF_6$, it remains constant at 4.95 ns till 300 kPa pressure and reduces to 4.39 ns at 400 and 500 kPa. This observation is quite interesting, since Toepler's theory shows that the formative time to breakdown of a gas gap is inversely proportional to the breakdown voltage of the gap (equation 3). Now, it is well known that the breakdown voltage of a gap is a function of the gas/gas mixture pressure as well as with the gas mixture concentration and therefore with changes in these parameters, the formative time lags to breakdown should be inversely varying with respect to these parameters. In spite of the value of the breakdown voltage being different at different gas/gas mixture pressures and different gas mixture ratios, the formative times remain practically analogous over the pressure range studied. A possible explanation is given below.

The delay time of a breakdown of a gas gap, $t_d$ consists of two components—the statistical component $t_s$, determined by the time required for the effective initial electron to appear in the gap and the formative time, $t_f$ required for the formation of discharge which doesn't depend on the electrode current from the cathode, i.e.,

$$t_d = t_s + t_f$$

For $E/p > 52.5$ kV/m-Pa (i.e., for gaps of the order of a millimeter or more), where E is the breakdown field strength and $p$ the gas pressure, the discharge formation time, $t_f$ consists primarily of the time required for a single avalanche to reach critical size, when the space charge field is equal to the external field. Here the avalanche becomes a streamer, which develops much more rapidly than the avalanche itself. The time required for this rapid development of the streamer in the gap is very small and is of the order of nanoseconds and in many cases it is ignored during calculations. In the present investigations, the gap under study is 0.20 mm which is very small and the observations of very small formative time lags (4.39–5.5 ns) is as expected. But, a possible reason behind the negligible change in the formative time lags with respect to the gas/gas mixture pressure and the gas mixture concentration may be that due to the very small gap, the time taken for the discharge to bridge the gap is practically the same at different gas pressures and gas mixture concentrations as explained earlier. From Table 1, it can be observed that the values in the formative time lags in pure $SF_6$, pure $N_2$ and $SF_6$-$N_2$ gas mixtures (at different mixture ratios) are very close. Considering the overall nature of the formative time lags in this gap, it can be assumed that the role of the formative time lags to breakdown in the discharge process is insignificant. These observations seem to closely agree with the results of Pfeiffer [13], which shows that for approximately uniform fields and small gap separations, the difference in the time lags (formative time) between $N_2$ and $SF_6$ does not seem to be very important.

In the case of 0.46 mm, it can be seen from Figures 3 and 4 that there is a continuous decrease in the formative time lag with increasing gas/gas mixture pressure and $SF_6$ concentration in the GIS bus duct. A similar observation can be made for the gap spacing of 0.61 mm from Figures

5 and 6. The formative time lag is a function of the breakdown voltage having an inverse relationship (equation 3). It is known that the breakdown voltage increases with increasing gas/gas mixture pressure and $SF_6$ concentration in $N_2$. Hence, a decrease in the formative time lags with respect to these parameters is observed when they are increased in the GIS at both gap spacings. It can be observed in Figures 3 and 5 that there is a wide difference in the formative time lags at different gas mixture pressures between pure $N_2$ and $SF_6$-$N_2$ mixtures. This is due to the large difference in the corresponding values of breakdown voltages. The lowest values of the formative time were observed in pure $SF_6$ at 500 kPa in both the gaps.

It can be further observed from Figures 3 and 5 that there is a steep decrease in the formative time lag when 10% $SF_6$ was added to $N_2$ in both the gaps, the steepness being more at higher pressures. This is as a result of the sudden and steep increase in the breakdown voltage when 10% $SF_6$ was added to $N_2$ in both the gaps. Beyond 10% $SF_6$ concentration, the steepness is observed to reduce and the formative time lags start to saturate at higher concentrations of $SF_6$ in the gas mixture at both gap spacings. The saturation occurs because the breakdown voltages of the gaps also tend to saturate beyond 40% $SF_6$ concentration in the gas mixture.

## 4.2 TOEPLER'S CONSTANT

An important parameter in Toepler's relation mentioned earlier is the Toepler's constant $k_t$, which gives an estimation of the formative time lags to breakdown for a particular gas gap and it is necessary while modeling the breakdown phenomena in a GIS. Using Toepler's relation in equation 3 and substituting the values of formative time lags ($t_f$) and the breakdown voltage (V)(Table 2) obtained from the present investigations, Toepler's constant is calculated for 0.46 mm and 0.6 mm gaps.

In the present investigations, it has been observed that the variations in the formative time lags to breakdown is small with respect to variations in the gas/gas mixture pressure and gas mixture concentration at the gap spacing of 0.20 mm [Table 1]. Therefore, the values of Toepler's constant were not calculated for this particular gap.

For 0.46 mm, it can be seen from the variations of Toepler's constant ($k_t$) in Figures 7 and 8 that the values of $k_t$ increase with increasing gas/gas mixture pressure (almost linearly) and $SF_6$ concentration in the bus duct. Similar observations can be made in the case of 0.61 mm gap also from Figures 9 and 10 and $k_t$ is seen to increase with respect to the gas/gas mixture pressure (almost linearly) and $SF_6$ concentration. In 0.46 mm, Toepler's constant lies in the range of $0.33\times10^{-4}$ Vs/cm–$2.75\times10^{-4}$ Vs/cm whereas it ranges from $0.33\times10^{-4}$ Vs/cm to $1.84\times10^{-4}$ Vs/cm in 0.61 mm over the experimental pressure range at different $SF_6$-$N_2$ gas mixture ratios. From Toepler's Law in equation (3), it can be seen that Toepler's constant is directly proportional to the product of the formative time lag and the breakdown voltage of the gap. The breakdown voltage of the gap increases with increasing gas/gas mixture pressure and $SF_6$ concentration in the bus duct, whereas the formative time lags decrease with the above parameters for the same gap length, but not in direct proportion to the variations in the breakdown voltage. Hence, $k_t$ will not remain constant with variations in the above parameters. In the present work, an increase in the Toepler's constant is observed for both the gaps. The lowest value of Toepler's constant is seen in pure $N_2$ and it increases to a maximum value in pure $SF_6$ in both the gaps.

The variations of the Toepler's constant with the $SF_6$ concentration in Figures 8 (0.46 mm) and 10 (0.61 mm) are similar to the variations of the breakdown voltage of the gaps with respect to the concentration of $SF_6$ at 0.46 mm and 0.61 mm, respectively (Table 2). The characteristics clearly exhibit a non-linear trend, which are more pronounced at higher gas pressures (400–500 kPa). There is a steep increase in the value of the Toepler's constant on addition of 10% $SF_6$ to $N_2$ at all pressures in both gaps with the steepness being more at higher pressures (400 and 500 kPa). This observation is as a result of the appreciable increase in the breakdown voltage of the gap on addition of 10% $SF_6$ to $N_2$. With further increase in the percentage of $SF_6$ in $N_2$, the increasing trend in the Toepler's constant starts decreasing and it almost saturates between 40% $SF_6$-60% $N_2$ mixture and pure $SF_6$. A similar trend can be observed from the characteristic of $SF_6$ concentration in $N_2$ with respect to the attachment coefficient ($\eta/p$) observed by various researchers [14]. In their results also, the values of attachment coefficient saturates when the $SF_6$ concentration in $N_2$ increased beyond 40%. Although, the results obtained by earlier researchers were under different theoretical and experimental conditions, the dependence of the effective ionization coefficient [$(\alpha$-$\eta)/p$, where $\alpha$ is the Townsend's first ionization coefficient] on the concentration of $SF_6$ in $N_2$ is similar in all the cases and thus it cannot be entirely neglected. It has been found that the breakdown voltage saturates when the percentage of $SF_6$ in an $SF_6$-$N_2$ gas mixture is increased beyond 40%. Since the breakdown voltage is a function of the effective ionization coefficient of the gas mixture, it may be concluded that the breakdown behavior with respect to the concentration of $SF_6$ will be similar. From this point of view, it may be appropriate to mention that Toepler's constant can be a function of the effective ionization coefficient [$(\alpha$-$\eta)/p$] of the gas/gas mixtures also.

## 5 CONCLUSIONS

THE present study dealt with the experimental measurements of the formative time lags to breakdown of a gap in a GIS. The validity of Toepler's spark law in analyzing the formative time lags with respect to the VFTO phenomena in a GIS was also investigated.

Taking into consideration the Toepler's constant approach to modeling the breakdown phenomena in a GIS, the range of Toepler's constant was evaluated at different gap spacings in the GIS using Toepler's spark law.

It has been observed that at a gap spacing of 0.20 mm, the formative time lags to breakdown of the gap in the GIS do not change significantly over a pressure range of 100–500 kPa at different concentrations of $SF_6$ in the $SF_6$-$N_2$ gas mixture. But at the other two gaps of 0.46 mm and 0.61 mm, significant variation in the formative time lags are observed with respect to the gas/gas mixture pressure and the $SF_6$ concentration in the gas mixture. The formative time lags have been found to decrease with increasing gas/gas mixture pressure and $SF_6$ concentration. At these gaps, the values of Toepler's constant were calculated using the Toepler's relation. Values of Toepler's constant in both these gaps were found to be dependent on the gas/gas mixture pressure and $SF_6$ concentration. The influences of these parameters on the value of the Toepler's constant are quite significant. The variations of the Toepler's constant with respect to the gas/gas mixture pressure and the $SF_6$ concentration in the GIS show an increasing trend. In this case also, the breakdown voltage is the major controlling parameter.

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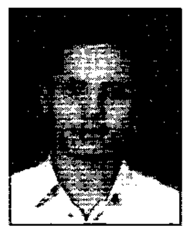
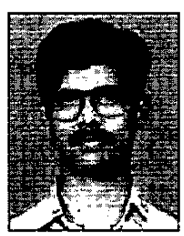


**Santanu Singha** received the B.E. degree in Electrical Engineering from Gauhati University, Assam, India in 1998 and a MSc degree in HV Engineering from the Indian Institute of Science, Bangalore, India in 2001. He is currently a Scientist at the General Electric Global Research Center, Bangalore, India. His primary research interests are in the areas of electrical insulation related to GIS, transformers, generators and circuit breakers.



**M. Joy Thomas** (M'95) received the Bachelor of Technology in Electrical Engineering from the Institute of Technology, Banaras Hindu University, Varanasi, India, the MSc and Ph.D. degrees in HV Engineering from the Indian Institute of Science, Bangalore, India. Presently, he is an Assistant Professor at the Department of HV Engineering, Indian Institute of Science, Bangalore, India. His areas of interest are GIS, EMC, EHV power transmission, pulsed power engineering and HV testing and measurements.