BREAKDOWN CHARACTERISTICS OF PLASMA CLOSING SWITCHES FILLED WITH DIFFERENT GASES

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ABSTRACT

When operating gas-filled plasma closing switches, the most commonly used dielectric gas is sulphur hexafluoride (SF_6) due to its desirable and advanced dielectric properties. In recent years, concerns over the impact of SF_6 on the environment and its contributions to the global greenhouse effect [1], as well as the continual rise in the cost of acquiring SF_6 [2] has led to a desire within the pulsed power community to find an alternative switching medium to replace SF_6, [3]. The main concern over replacing SF_6 is that plasma closing switches filled with any replacement gas must have similar performance parameters to the SF_6–filled switches, e.g. parameters such as the DC breakdown voltage and the triggered breakdown voltage, jitter and breakdown voltage spread, the recovery of the switch and the energy losses [4]. This paper presents results obtained for DC breakdown tests in a self-breakdown switch with an adjustable inter-electrode gap that has been filled with argon, nitrogen, atmospheric air and an argon/oxygen mixture at different pressures. As a result of the experimental work conducted, the characteristics of the plasma closing switches filled with different gases have been obtained and compared to previous work carried out [5] as well as compared with the characteristics of commonly used SF_6–filled switches. Initial development of the model of a plasma closing switch has been developed which will be developed so that the model can be used for characterising the performance of different pulsed power systems and for optimization of current systems in order to improve their performance parameters e.g. decrease jitter and pre-fire rate, generate tailored wave-forms and improve overall stability of operation.

1. INTRODUCTION

The desirable dielectric properties of SF_6 such as the ability to withstand voltages 3 times that of air [1] and the short amount of time required after breakdown occurs to recover nearly full pre-breakdown strength, amongst other reasons means that SF_6 is the main gas of choice in many areas of the pulsed power industry and research.

Since the Kyoto protocol classed SF_6 as a greenhouse gas with global warming potential (GWP) 22,500-24,900 and an atmospheric lifetime in the region of 800-3,200 years [6], research has been conducted into minimising SF_6 usage throughout industrial applications by mixing small percentages of SF_6 with other gases [7] with a view to replacing SF_6 with a suitable alternative gas. Most of the gases tested that have shown a similar or higher dielectric strength than SF_6 have also been greenhouse gases or damaging to the environment, therefore will not be used as a replacement for SF_6. Ideally nitrogen, oxygen or some mixture of the two gases will show dielectric properties comparable to those displayed by SF_6 and thus could be used to replace SF_6 in research and within industrial applications. Another gas of interest that is also currently employed in industrial applications is a 90% Argon - 10% Oxygen mixture.

2. EXPERIMENTAL WORK

2.1 Self-breakdown switch design

From specifications provided by the industrial partners, a self-breakdown switch was designed and constructed.

The body of the switch itself is black PVC tubing 102mm in diameter and can be pressurised up to a maximum of 4 bar (gauge) pressure. The electrodes used within the switch are spherical brass ball bearings each 16mm in diameter. The bottom electrode is grounded while the top electrode experiences the charging voltage applied to it through a high voltage connection in the top of the switch body the inter-electrode spacing can be adjusted from 0mm (touching) to a maximum of 9mm gap spacing. Also present in the switch body design is a 25mm diameter quartz window mounted into the side of the switch body (Fig. 1) to allow for optical diagnostics of the plasma channel.

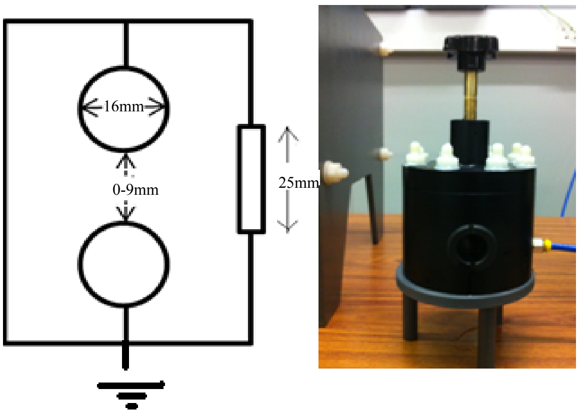

Fig 1. Schematic drawing of the test-cell with dimensions and a photograph of the constructed switch.

2.2 Experimental Set-up

The inter-electrode gap space was set to 1mm before the test chamber was evacuated using a vacuum pump. The test-cell was then filled with compressed air to 0 bar (gauge) pressure before the voltage was manually increased using a high voltage DC power supply connected through a 100kΩ resistor. A North Star PVM-5 high voltage probe (60kV DC/ 100kV impulse) and Tektronix digitising oscilloscope were used to monitor breakdown voltages. The DC voltage applied across the test cell was increased manually until a breakdown occurred in the test cell. 20 breakdowns were measured and the test cell was then evacuated again before being filled to 0.5 bar (gauge pressure) and the breakdown shots repeated. After each set of 20 breakdowns the test cell was evacuated with a vacuum pump before the pressure was increased in 0.5 bar increments up to a maximum of 4 bar (gauge) pressure. These breakdown tests were repeated at each of the gas pressures for each gap spacing 1mm-9mm (in 1mm increments) and also for each of the 4 gases/gas mixtures (oxygen, nitrogen, 60% oxygen 40% nitrogen and 10% oxygen – 90% argon).

The gas was supplied to the test cell via a gas distribution board leading to a gas connection in the side of the switch body. The gas distribution board allowed for evacuation of the test cell, re-pressurising of the test cell and monitoring of the gas pressure within the test cell.

2.3 Experimental Results

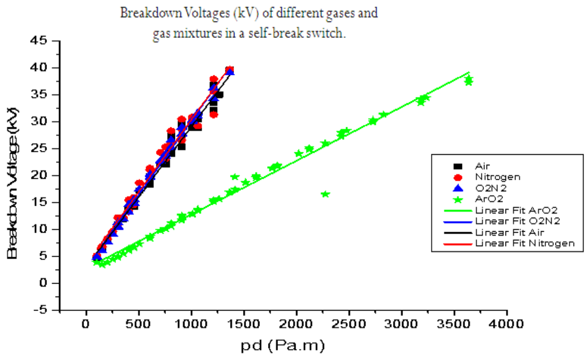

Fig.2 .Self-breakdown results for all 4 gases tested.

The results obtained for the self-breakdown tests are shown in Fig 2. above and upon evaluation, it is apparent that in general the breakdown voltages for each of each gap spacing and pressures tested the breakdown voltages obtained are fairly stable with no apparent conditioning effects. The exception to this was seen in the breakdown voltage test results of the Argon-Oxygen mixture in which the breakdown voltages obtained from experiment were largely unstable. For all gases and gas mixtures tested breakdown voltages increase as the product of pressure and distance, *pd* increases.. The standard deviation of breakdown voltages obtained in these experiments decreased as the gap spacing between the electrodes was increased.

A linear fit was plotted onto the graph of experimentally obtained results to determine whether the increase in the breakdown voltage with increase in pd was in fact a linear relationship (the field enhancement on the surface of the electrodes was evaluated using an electrostatic solver QuickField and deemed to be insignificant). Table 1 shows the values of the coefficients of the linear equation $y = ax + b$ plotted where a is the gradient of the fit (in kV/Pa.m) and b is the minimum breakdown voltage (measured in kV). The R^2 values quoted are a way of measuring how close to a linear fit (when R^2=1) the obtained experimental results are.

	A (kV/Pam)	B (kV)	R^2
Air	0.0261	3.0206	0.9849
Nitrogen	0.0268	3.6222	0.97222
60% Nitrogen 40% Oxygen	0.0274	2.7672	0.9939
90% Argon 10% Oxygen	0.01	2.8085	0.9786

Table 1. Coefficients of the equation y=ax+b and the R^2 values when a linear fit is applied to the experimental results.

The mixture of Nitrogen and Oxygen had the largest R^2 values, while pure Nitrogen showed the smallest of the R^2 values i.e. a linear fit is more accurate in describing the Nitrogen-Oxygen results than describing results obtained using pure Nitrogen.

2.4 Plasma Channel Resistance

As part of this research a resistance of post-breakdown plasma channel has been evaluated. This resistance defines energy losses and character of the transient plasma process in plasma closing switches.

Therefore it is important to evaluate the plasma resistance for different gases and electrode topologies. The values of the transient plasma resistance will be used in the analytical investigations of the performance of multi-stage Marx generators. In order to be able to evaluate the plasma resistance of the switch, an RLC circuit has been designed and the plasma channel (developed after the closure of the switch) was used as a resistive load in this circuit. The value of the capacitor was 45 nF and the switch was energised with a DC voltage. As soon as breakdown channel is formed between the switch electrodes a transient process is observed in the RLC circuit and the oscillating current was monitored using a Pearson current monitor. The resistance of the circuit consists of two components – the resistance of the circuit elements, $R_{circuit}$, and the resistance of the plasma channel, R_{plasma}. In this work it was assumed that the plasma resistance is a constant and therefore the transient sinusoidal current is described by the following equations

$$I = I_0 \exp(-\alpha t)\sin(\omega t) \quad (1)$$

where I_0 is a constant which is related to a maximum peak current (A), α is the attenuation constant (1/sec) and ω the angular frequency (in rad/sec). The transient current was measured for 4 inter-electrode distances: 0.125mm, 0.25mm, 0.5mm and 0.75mm.

Equation (1) describes the transient current well as can be seen in Fig.3 below which shows the experimental current waveform for 0.125mm and the corresponding analytical transient current waveform. The inductance and resistance of the plasma channel change over time which may well explain the poorer fit in the first quarter of current oscillation.

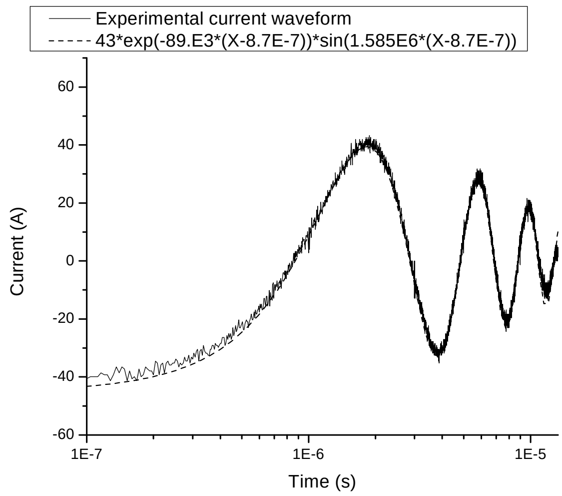

Fig 3. The current waveform at 1/8mm gap.

Three waveforms for each gap spacing were obtained and an average values of α and ω taken to calculate the average inductance

$$L = \frac{1}{\sqrt{\omega_0^2 C}} \quad (2)$$

of the circuit and total resistance:

$$R_{TOT} = R_{circuit} + R_{plasma} = 2\,L\,\alpha \quad (3)$$

It has been shown that the radius of the anode spot formed by the plasma channel in air increases proportionally to time during the first 100-150 μs [8]. Assuming that the energy deposition into the plasma channel is a continuous process and this energy is also directly proportional to time as suggested in [8], the radius of the plasma channel is directly proportional to the energy delivered into the channel, E. Therefore, the plasma resistance R_{plasma}, for any specified gap length is given by

$$R_{plasma} = k\frac{l}{E^3} \qquad (4)$$

Where l is the gap length and k is the ratio of the change in resistance at different gap lengths to their energies. k is given by

$$k = \frac{\Delta R_{TOT}}{\left(\frac{l_1}{E_1^3} - \frac{l_2}{E_2^3}\right)} \qquad (5)$$

where ΔR_{tot} is a difference between two total resistances for two different inter-electrode gaps. Therefore, the constant resistance of plasma for each inter-electrode gap can then be calculated:

$$R_{plasma} = R_{tot} - R_{circuit} \qquad (6)$$

Using the above method, values for the plasma resistance have been obtained for 4 inter-electrode gaps. These values are listed in the table below, the observed reduction in plasma resistance with an increase in the inter-electrode distance can be explained by higher breakdown voltages (thus higher energy delivered into plasma) for larger gap spacings.

Gap Spacing (mm)	R_{plasma} (mΩ)
0.125	806
0.250	265
0.500	65
0.750	8

3. DISCUSSION

A self-breakdown switch with similar topology to those currently employed within the pulsed power industry has been designed, constructed and tested for different inter-electrode distances and when filled with different gases at different pressures. The 4 gas/gas mixtures tested were chosen with a view to finding a suitable alternative to SF_6 which is currently the gas of choice and employed throughout much of the pulsed power industry.

The nitrogen-oxygen mixture provided the most stable breakdown results and also had the most linear increase in breakdown voltage as the pressure within the switch and inter-electrode distance increased.

The plasma resistance defines energy losses in the switch and the characteristics of transient plasma process in plasma closing switches. The plasma resistance has been evaluated for the switch at different inter-electrode spaces and these values will aid in the development of a model that can be used to characterise the performance of different pulsed power systems as well as be used in the optimization of currently employed systems to improve certain key performance parameters.

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