J. Phys. D: Appl. Phys. 26 (1993) 954–958. Printed in the UK

The operation of repetitive high-pressure spark gap switches

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Received 19 October 1992, in final form 2 February 1993

Abstract. Two parallel experiments have been undertaken to investigate the mechanisms which govern the recovery of spark gap switches in repetitive applications. Measurement of the neutral gas density is accomplished using a laser Schlieren technique which enables spatial and temporal cooling of the gas to be observed. The rate of rise of voltage recovery is recorded using a double-pulse modulator system which determines the breakdown voltage of the gas at specific time intervals after breakdown by the first pulse. A continuous sweep voltage is applied to the switch in order to establish the influence of ions on the recovery characteristics. Results are presented for SF_6 and air which show that voltage recovery is not solely governed by recovery of neutral gas density. There is a significant influence from the residual ion population created by the previous discharge. This influence is dominant for several hundred milliseconds after breakdown. The application of a suitable sweep voltage has been shown to effectively minimize the ion population, which results in significantly improved voltage recovery characteristics.

1. Introduction

High-pressure spark gap switches are found in many pulsed power applications and high-voltage systems. They display desirable switching characteristics, such as nanosecond closing times, wide voltage and current handling capability (up to MV and MA levels), low jitter and the ability to be pulse-charged to several times the DC breakdown voltage. However, the spark gap switch performs poorly under repetitive operation due to the limited inter-pulse rate of voltage recovery, which restricts the maximum repetition rate to a few hundred hertz without introducing any form of gas flow. The temperature of the gas in the switching column can rise to several thousand kelvin during conduction, resulting in severe reduction in gas density. This has the effect of increasing the local value of E/N of the gas (E is the electric field strength, N is the number density), and therefore reducing the breakdown voltage for a significant time after the switching event. Before the voltage can be re-applied, the gas in the inter-electrode volume must be allowed to cool to a level approaching its pre-breakdown temperature. Until this is achieved, the switch will display a breakdown voltage which is reduced relative to the DC and pulsed charged operating level.

Recent investigations [1–4] into the repetitive operation of spark gaps have led to some degree of understanding of the nature of the recovery processes and three distinct phases have been suggested.

(i) Removal from the insulating gas of any residual ionization by recombination, attachment, de-excitation and so on. This is assumed to occur in the first few tens of microseconds after switching.

(ii) Recovery of the neutral gas density in the switch to a level approaching its pre-breakdown value. This is believed to take a few milliseconds.

(iii) Recovery of the capability of the switch to be over-volted relative to its static breakdown voltage, which can take up to a few seconds.

The processes governing this latter phase of recovery are as yet unexplained and may cause an intermediate plateau in the voltage recovery curve. Similar voltage recovery characteristics have been observed [5–7] to occur in circuit breakers after current zero. These effects were attributed [6] to energy being transferred to the gas during recombination and it was suggested that this release of energy maintains the arc channel region at a relatively high temperature. Although it is difficult to make direct comparisons between the voltage recovery curves obtained for circuit breakers and those associated with repetitive switches, it is possible that delayed recombination of the gas will ultimately limit the rate of voltage recovery, provided that this recovery is solely dependent upon gas density.

In order to identify the individual mechanisms which are responsible for overall voltage recovery of the switch, two parallel experiments have been undertaken. The first involves measurement of the neutral gas density

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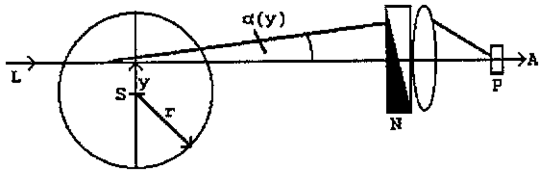

Figure 1. Schematic diagram of the laser Schlieren system.

after breakdown to establish its influence on voltage recovery. The second utilizes a high-voltage double-pulse generator which enables the rate of rise of voltage recovery to be determined. The two experimental arrangements are described below.

2. Experimental

2.1. Gas density measurements

Quantitative measurement of gas density after breakdown is achieved using a laser Schlieren technique [8, 9]. An array of laser beams probe the inter-electrode region, each at a known radius from the spark axis, as shown in figure 1. After switching, the fluctuations in gas density due to the shockwave and hot arc remnants are observed to move radially outward from the spark location. The change in density gives rise to a change in refractive index which results in deflection of the laser beams. Measuring this angle of deflection enables calculation of the refractive index $n(r)$, which can in turn be used to find the neutral gas density $N(r)$ via the Gladstone–Dale relation [9].

Referring to figure 1, four 5 mW He–Ne lasers are used to probe the switch volume from different directions, each at specific radial positions from the spark axis (S). The light from each laser (L) illuminates a neutral glass wedge (N), which has a varying optical density across its surface. The light transmitted through the wedge is focused onto a photodiode (P) to produce a voltage signal. This voltage is amplified (A) to provide the final detector output. When the beam is deflected, there is a change in the transmitted light intensity which is recorded by the photodiode and is observed as a change in detector output voltage. The voltage change can be related to the angle of deflection via a simple calibration procedure.

The detector signals provide the angle of deflection at each radial position for a given time after breakdown. This gives the Schlieren deflection curve $\alpha(y)$ which is used to calculate the refractive index, $n(r)$, using a method of analysis derived by Kogelschatz and Schneider [10]. This process is repeated for a number of different times after breakdown, allowing the gas cooling to be observed. A method of averaging is employed to overcome the considerable degree of scatter in the deflection profiles between successive closures of the switch. A more thorough description of this system and method of analysis is given in [11, 12].

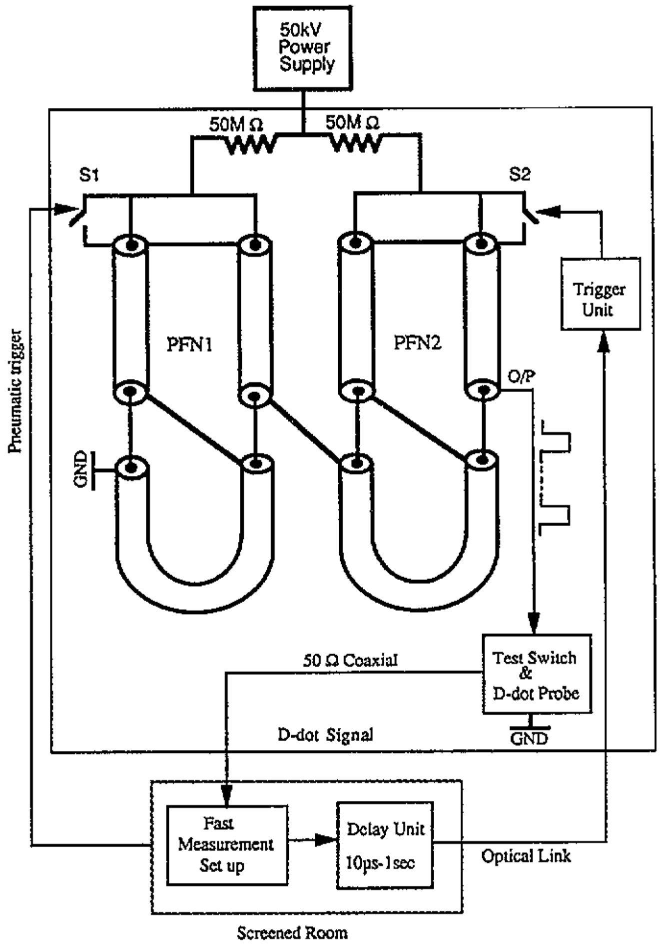

Figure 2. Schematic diagram of the double-pulse modulator.

The switch used in the present study is housed in a purpose-built octagonal pressure vessel, and consists of two plane aluminium electrodes of diameter 80 mm and gap spacing 7 mm with field-enhancing pins located at the centre of each in order to maintain a constant spark position between shots. A stacked Blumlein cable generator [13] is used to deliver a negative voltage pulse of up to 150 kV to the switch. The rise time and duration of the voltage pulse are 20 ns and 100 ns respectively.

2.2. Voltage recovery measurements

The rate of rise of voltage recovery is measured by applying two voltage pulses to a test switch of the same dimensions as that used for the gas density measurements. The first voltage pulse causes breakdown of the switch and the second voltage pulse determines the rate of rise of recovery voltage. The double-pulse modulator is capable of providing two discrete high-voltage pulses each of 100 ns duration, with a variable inter-pulse time in the range 10 μs–1 s. The system can deliver individual pulses of up to 150 kV peak of either polarity.

A schematic diagram of the system is shown in figure 2. The modulator consists of two pulse-forming networks (PFNs). PFN1 and PFN2 are Blumlein cable generators which are stacked to a level of two and thus provide an open-circuit voltage of four times the DC charging voltage. A comprehensive description of these

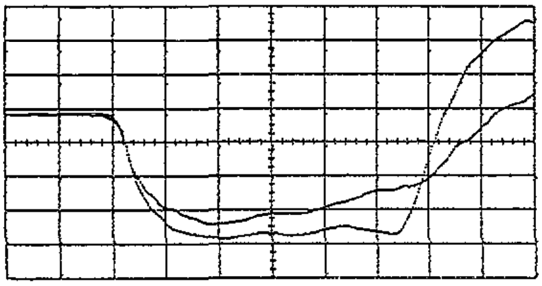

Figure 3. A typical pair of output pulses (superimposed) from the double pulse modulator. (35 kV per division, 20 ns per division).

networks is given by Somerville *et al* [13]. Both networks are connected in series and operated independently of each other by switches S1 and S2. Switch S1 is fired via a pneumatic gas release system from a screened enclosure and switch S2 is a trigatron-type spark gap fired on command by the trigger unit. The trigger/delay generator consists of a low-voltage variable time delay generator, a fibre-optic link, and a trigger voltage generator.

The voltage pulses are monitored using a fast D-dot probe incorporated into the switch [19]. The probe consists of a flat plate of 1 cm diameter which is flush-mounted in the earthed electrode. It is isolated from the electrode by an annular gap which is 0.5 mm wide and this also acts as a protection gap should breakdown to the probe occur. The output signal produced by the probe is proportional to the average rate of change of the electric flux density (D) over the plate surface and is used to observe the voltage waveform; this signal is integrated using an RC passive integrator (τ = 300 ns) and recorded on an HP54112D digitizing oscilloscope.

A typical pair of output pulses with a 1 ms inter-pulse time are shown superimposed in figure 3. Both pulses have a rise time of around 20 ns and a duration of 100 ns. The second pulse is slightly reduced in magnitude as it is generated from a non-inverting Blumlein winding arrangement which has a lower operating efficiency than that of the inverting type [13].

3. Results and discussion

The rate of rise of neutral gas density and hold-off voltage were measured in a 7 mm gap filled with SF_6 to a pressure of 0.5 bar. The DC breakdown voltage under these conditions was found to be 30 kV. This value is slightly below the theoretically predicted level (31.5 kV) and the discrepancy is thought to be attributable to the slight degree of field non-uniformity caused by edge effects associated with the D-dot probe.

In both experiments the initial voltage pulse applied to the gap was 90 kV, resulting in the switch being overvolted by approximately 300%. This enabled the three suggested phases of recovery described earlier to be investigated.

After high-voltage breakdown of the switch, the neutral gas density, shown in figure 4, is observed to recover to 90% of its pre-breakdown value in approximately 1 ms. The gas density recovery curve shows a relatively smooth increase with time to the pre-breakdown level. The voltage recovery curve obtained with the double-pulse system, under the same experimental conditions, is shown in figure 5. These results clearly indicate that voltage recovery occurs in three distinct phases.

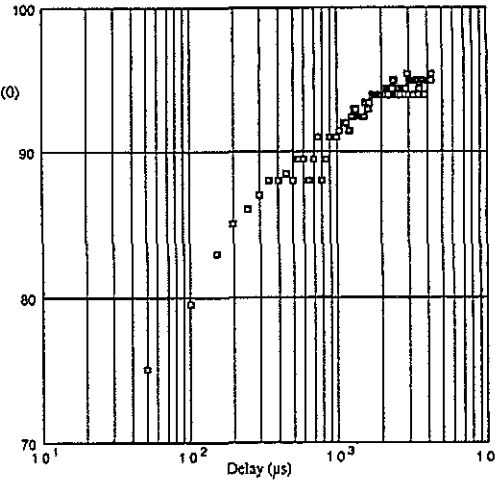

Figure 4. Recovery of the neutral gas density in SF_6, for a 7 mm gap at a pressure of 0.5 bar, where $N(0)$ is the ambient level.

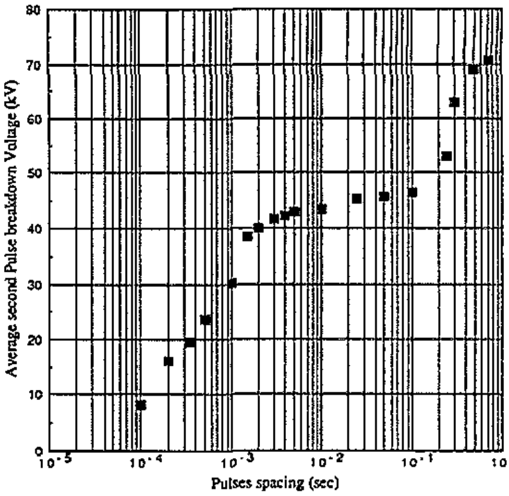

Figure 5. Rate of rise of recovery voltage in SF_6, for a 7 mm gap at a pressure of 0.5 bar.

Initially, the switch hold-off voltage (figure 5) is seen to increase with time up to approximately 1 ms after breakdown. At this point an intermediate level is reached at which the hold-off voltage remains constant for a few hundred milliseconds. This level is usually described as the 'plateau' and has been observed by other workers [2, 4]. Although the hold-off voltage of the switch during the plateau region exceeds the DC breakdown voltage, the actual voltage level at which the plateau occurs is specific to the experimental conditions. For example, with slowly rising pulsed charged voltages or under DC conditions, this level can be below the static breakdown voltage of the switch. The final stage in the recovery characteristic displays a hold-off voltage which increases with time, up to the initial pulsed charged self-breakdown voltage of the switch (300% of the DC level).

When the gas density curve (figure 4) is compared with the rate of rise of recovery voltage (figure 5), there is an obvious disparity if the recovery voltage is assumed to be solely dependent upon gas density. This indicates that the 'plateau' observed in the voltage recovery characteristic of figure 5 is not attributable to a corresponding plateau in the recovery of gas density and must therefore be associated with some other influence.

Previous research into the mechanisms of discharge initiation in electronegative gases, such as SF_6 and air [14–17], has shown that there is a strong correlation between the negative ion population and the probability of discharge inception. Free electrons, formed by background radiation and cosmic rays, are readily attached to neutral gas molecules to form negative ions. These ions have relatively long lifetimes and can play an active role in the production of initiatory electrons for discharge inception through the process of collisional detachment. In the nanosecond regime, MacGregor *et al* [17] found that the presence of either positive or negative ions strongly influenced the probability of discharge inception and therefore the breakdown level under pulsed charged conditions.

Upon consideration of these findings, together with the fact that a large number of negative ions will be produced as a result of the first pulse breakdown, it was thought appropriate to establish the ion influence in this study. Although ion concentrations were not measured, it is reasonable to assume that a large population could exist in the gas after switching and this will significantly affect the probability of discharge inception during application of the second voltage pulse.

A continuous sweep voltage of 2 kV was applied to the switch in order to deplete the negative ion population by sweeping them from the inter-electrode volume. A comparison of the results obtained with and without the sweeping bias is shown in figure 6. It can be seen quite clearly that there is a significant increase in the rate of rise of voltage recovery with the sweep voltage present, and also there is now no evidence of an intermediate 'plateau'. This indicates that the sweep voltage is effectively removing negative ions from the gas volume and thereby significantly increasing the second pulse breakdown voltage by depleting the major source of initiatory electrons.

Further work was undertaken in air at 1 bar, with and without a sweep voltage present, using a pulsed charged voltage of approximately three times the DC breakdown level. The results, shown in figure 7, once more indicate that by depleting the ion population, it is possible to obtain significantly improved pulsed voltage recovery characteristics.

The relationship between ion mobility, electrode spacing and sweep voltage will control the rate of removal of negative ions from the switch. For different operating conditions (pressure, spacing, repetition rate) it is possible to calculate the magnitude of the sweep voltage required for optimum voltage recovery. In these experiments, improvement in voltage recovery rate is observed after a delay of several hundred microseconds, which is consistent with published data on the mobility of negative ions in SF_6 and air [14, 18].

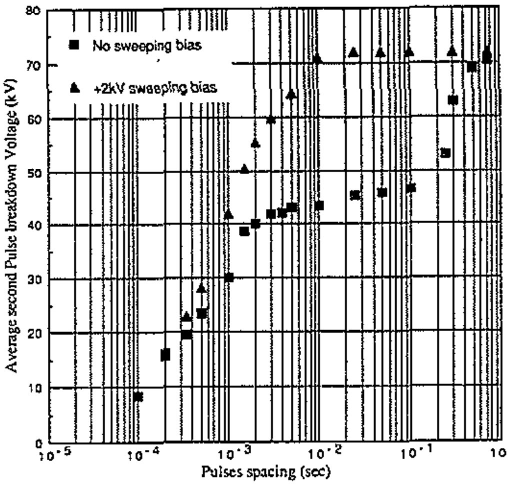

Figure 6. Rate of rise of recovery voltage in SF_6 with and without a sweeping bias, for a 7 mm gap at a pressure of 0.5 bar.

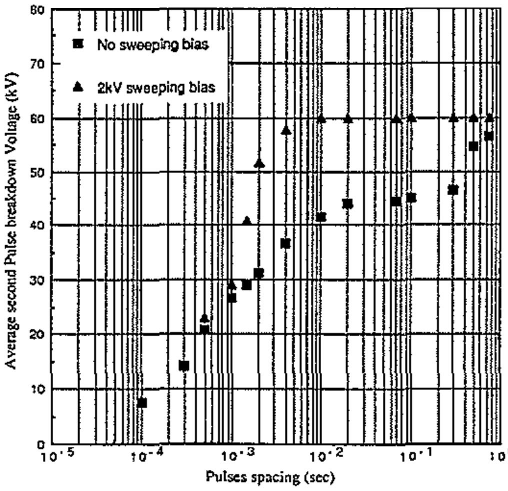

Figure 7. Rate of rise of recovery voltage in air with and without a sweeping bias, for a 7 mm gap at a pressure of 1 bar.

4. Conclusion

Comparison of the recovery of neutral gas density with the rate of rise of recovery voltage in electronegative gases has identified that the negative ion population has a major influence on the operation of high-pressure spark gaps under repetitive conditions. By using a suitable sweep voltage during the inter-pulse period, the negative ion population can be reduced to a level which extends the operation of repetitive spark gaps into the kilohertz regime. Although these results are limited to the experimental conditions discussed above, it is intended to extend the investigation to determine the effect of other parameters such as charge transfer, peak current and voltage, gas pressure and gas type.

Further improvements in repetition rate may be possible by using suitable gas mixtures which possess higher ion mobilities. Alternatively, it may be possible to profile the waveshape of the applied voltage to 'self-sweep' the gap of negative ions during charging. For higher repetition rates non-attaching gases may have to be used. In this case, it may be necessary, under certain experimental conditions, to control the residual positive ion population and gas purity.

Acknowledgments

This work is supported by the UK Science and Engineering Research Council and the UK Ministry of Defence.

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