

Over Recovery in Low Pressure Sparkgaps—Confirmation of Pressure Reduction in Over Recovery

K. V. Nagesh, P. H. Ron, G. R. Nagabhushana, and R. S. Nema

Abstract—The *over recovery* in sparkgaps [1], [2] operating along the left-hand side of Paschens' characteristics is due to pressure reduction in the gap after the first pulse discharge. This pressure reduction leading to over recovery in low pressure sparkgaps has been verified using a low pressure sparkgap with two sparkgaps placed one above the other in the same chamber. The breakdown voltage strength characteristics of the second gap has been determined for gap spacings of 3.5 mm to 10 mm, diffusion of plasma in the direction of vacuum pumping and opposite, at a pressure of 2.1 Pa for hydrogen gas. The vacuum pumping direction has a great influence on the breakdown strength characteristics of second gap after the first gap discharge. The breakdown voltage of the second gap can exceed its self breakdown voltage only 1) when the diffusion of plasma and vacuum pumping direction are same and 2) when the second gap spacing is greater than or equal to first gap spacing. Shorter gaps can always have breakdown voltage lower than or equal to their self breakdown voltage. The experimental setups, behavior of self breakdown voltages of second gap due to breakdown in the first gap, over recovery characteristics of sparkgaps, the results, and discussions are presented here.

Index Terms—Gas sparkgaps, low pressure discharges, low pressure sparkgaps, over recovery, pressure reduction in over-recovery, recovery times, sparkgap recovery, sparkgaps.

I. INTRODUCTION

THE recovery of the sparkgap between the first and subsequent pulses is a very important phenomenon in repetitive pulsed sparkgaps. The low pressure sparkgaps recover to greater than their breakdown voltages of first pulse (FPBDV) under certain conditions, and it is called *over recovery* in these studies [1], [2]. This over recovery is due to pressure reduction in the gap after the first pulse discharge. The experiments to measure the pressure in the gap after discharge are very complicated. However, the changes in pressure after the discharge can be measured by 1) microwave interferometer rated 100 GHz [3] or 2) laser interferometer [4] by scanning the gap volume. Presently, the pressure reduction in low pressure sparkgaps has been verified using a low pressure sparkgap with two sparkgaps placed one above the other in

the same chamber and reported here. The breakdown voltage characteristics of the second gap influenced by the discharge of the first gap has been determined for gap spacings of 3.5 mm to 10 mm, diffusion of plasma in the direction of vacuum pumping and opposite, at a pressure of 2.1 Pa for hydrogen gas. A two pulse system has been used to study these breakdown voltage characteristics of low pressure sparkgaps with two gaps. The first pulse is used to initiate discharge in one of the gaps and a similar second pulse is used to probe the voltage strength status (after discharge) in the other gap. The first pulse discharge produces plasma in the sparkgap. This momentarily increases the gap pressure and temperature to $\sim 1.6 \times 10^5$ Pa [5] and ~ 5000 K [6] in the discharge column. The plasma expands and diffuses in all direction. The pressure in the gap volume of the sparkgaps reduces below the normal operating pressure inversely to the temperature of the plasma. If the plasma expansion supported by vacuum pumping dominates the gas inlet, the pressure in the gap volume reduces below normal pressure and results in over recovery in the same gap. It results in breakdown voltage of the second gap changes to greater than its normal self-breakdown voltage. It is assumed that all ionizations from the discharge in the gap volume are diffused to the walls by this time. If the temperature and pressure have been reduced to normal by the time ionizations are diffused, it results in the full recovery of the same gap. It results in breakdown voltage of the second gap changes to nearly the same as its normal self-breakdown voltage. It results in under recovery for delay times lower than the above, wherein the pressure in the same gap is higher than the normal or the leftover ionizations leads to breakdown at lower voltages. It results in breakdown voltage of the second gap changes to less than its normal self-breakdown voltage for periods of up to 10 ms. The effect of gap spacing and gap pressure on the breakdown voltages of the low pressure sparkgaps (with single and two gaps) have been studied and reported here.

II. EXPERIMENTAL SETUP

The cross-sectional view of the low pressure sparkgap with two gaps is shown in Fig. 1. The experimental setup, the sparkgap assembly, measurement of voltages and currents are similar to the one used for *over recovery* studies with single sparkgap [1], [2]. The two sets of sparkgaps are assembled in the same chamber with one set above the other (60 mm

Manuscript received December 22, 1998; revised September 9, 1999.

K. V. Nagesh and P. H. Ron are with the Accelerator and Pulse Power Division, Bhabha Atomic Research Centre, Trombay, Mumbai, 400085 India (e-mail: kvnag@magnum.barc.ernet.in).

G. R. Nagabhushana and R. S. Nema are with the Department of High Voltage Engineering, Indian Institute of Science, Malleswaram, Bangalore, 560012 India.

Publisher Item Identifier S 0093-3813(99)09853-7.

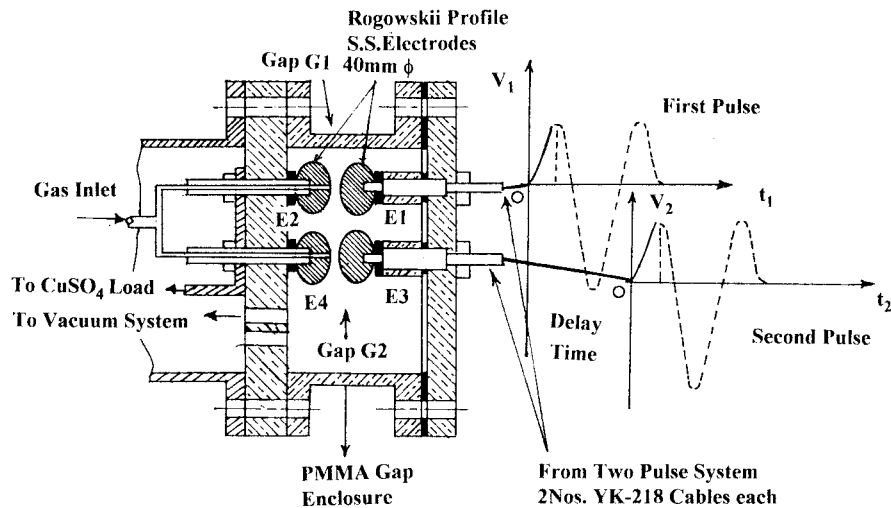


Fig. 1. Experimental chamber of low pressure sparkgap with two sparkgaps.

between central axis of electrodes), at the center of polymethyl methacrylate (PMMA) chamber (150 mm diameter, 100 mm height). The stainless steel sparkgap electrodes (40 mm diameter, 10 mm thick) are of Rogowski profile, machined on a CNC lathe, for a uniform electric field between electrodes. Two YK-218 cables (65 kV, 20.9 Ω , 250 pF/m, 8 m length each) are connected to each pair of electrodes $\{E1\&E3\}$ through PMMA insulator and a copper tube for co-axial return path. These two YK-218 cables are connected to the respective Tesla transformers at the other ends. All the four cables are connected to same sparkgap in case of recovery experiments of a particular sparkgap. The voltage pulses are applied to the respective sparkgaps through these cables. The outputs of these sparkgaps are terminated with copper sulphate load of 5.2 Ω . High purity Iolar-2 hydrogen gas is used in these experiments. The gas is let in through the central hole of the electrodes $E2$ and $E4$. The experimental chamber evacuated to 1.3×10^{-3} Pa is filled with the required gas up to ~ 133 Pa pressure and evacuated again to 1.3×10^{-3} Pa before starting the experiments. This flushing process is repeated four times to maintain the purity of gas.

III. EFFECT ON BREAKDOWN VOLTAGE DUE TO FIRST PULSE DISCHARGE

A. Discharge Plasma Diffusion in the Direction of Pumping

Fig. 2 shows the sequence of breakdown and plasma movement processes in a low pressure sparkgap with two sparkgaps, with first pulse applied to the top gap electrode $E1$ and second pulse to the bottom gap electrode $E3$. The typical Paschen's characteristic is shown in Fig. 3. The possible ways the breakdowns in gap $G2$ is effected are 1) the ultra violet and other lights from the discharge in $G1$ illuminates $G2$ and hence causes some ionizations which reduces the breakdown voltage of $G2$ in nanoseconds range, 2) the ions from $G1$ also enters $G2$ and reduces the breakdown voltage of $G2$ in microseconds range, and 3) shockwaves due to discharge in $G1$ also causes fluctuation of pressure in the gap $G2$. This can increase or decrease the breakdown voltage of $G2$ in hundreds

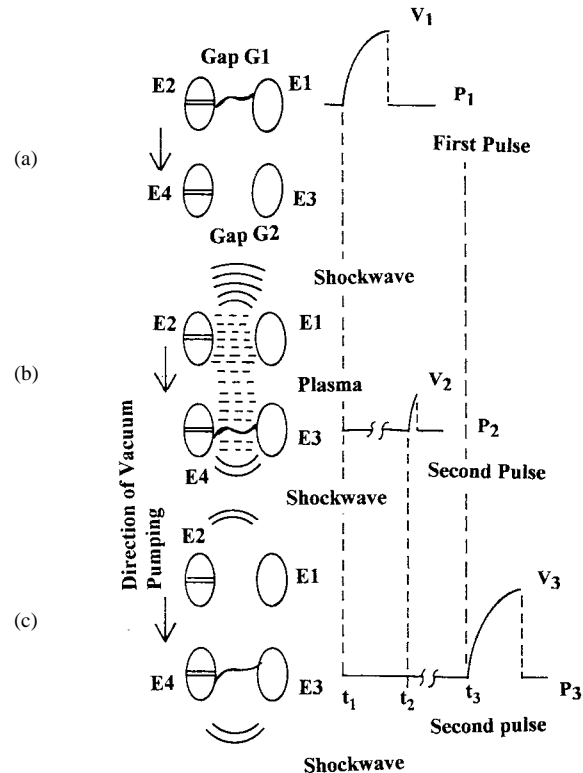


Fig. 2. Breakdown and plasma movement processes in low pressure sparkgap with two sparkgaps, diffusion in the direction of pumping.

of microseconds to a few milliseconds range. In the present low pressure sparkgap recovery experiments, the shockwaves play a major role since the recovery times are in the range of hundreds of microseconds to a few milliseconds [1], [2]. The shockwave velocity is the combined effect of discharge in sparkgap and the direction of vacuum system pumping. When the first pulse is applied to gap $G1$, the velocity is higher compared to the case of first pulse applied to the gap $G2$. The first pulse is applied to the gap $G1$ at a time t_1 and having a pressure of P_1 . This gap breaks down at a voltage V_1 as shown in Fig. 2(a), (point A on Fig. 3) and produces plasma

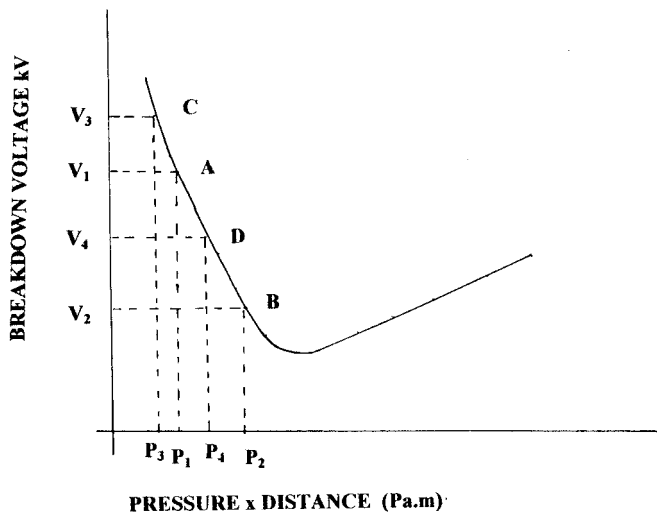


Fig. 3 Typical Paschens' characteristics of low pressure sparkgap.

and shockwaves in the gap as shown in Fig. 2(b). This results in an increase in temperature and pressure in the gaps. The plasma starts diffusing to the walls resulting in decrease in temperature and pressure of the gap. The breakdown behavior of the gaps changes due to diffusion of plasma to the walls. The pressure in the gap $G2$ reduces to P_2 at a time t_2 . If the second pulse is applied at this instant t_2 , the gap breaks down at a voltage $V_2 < V_1$ (point B on Fig. 3). This shows that the gap G_2 has been affected due to discharge in G_1 . At this time the gap G_2 has not returned to its pre-breakdown status. If the second pulse is applied to the gap G_2 at a later instant t_3 , with the pressure $P_3 \leq P_1$ (Fig. 2(c), point C on Fig. 3) and results in breakdown at a voltage $V_3 > V_1$. Since there are no previous discharges in G_2 , the changes in breakdown voltage $V_3 > V_1$ is possible only with change in pressure in the gap due to Paschen's characteristics. This demonstrates that the only pressure reduction in the gap results in breakdown voltages higher than the first pulse breakdown voltages after the first pulse breakdown. When the breakdowns are in the same gap, the pressure reduction in the gap results in breakdown voltages higher than the first pulse breakdown voltages during the recovery period and it is called *over recovery* in low pressure sparkgaps.

B. Discharge Plasma Diffusion in the Opposite Direction of Pumping

Fig. 4 shows sequence of breakdown and plasma movement in low pressure sparkgap with two sparkgaps, with first pulse applied to the bottom gap $E3$ and second pulse to the top gap $E1$. The first pulse is applied at a time t_1 with a pressure in the gap P_1 to the gap $G2$ as shown in Fig. 4(a). This gap breaks down at a voltage V_1 and produces plasma and shockwaves in the gap as shown in Fig. 4(b) (Fig. 3, point A). This increases the pressure and temperature in the gaps. This plasma starts diffusing to the walls and the self breakdown voltage of the second gap starts increasing with reduction in pressure in the gap. The pressure in the gap $G1$ decreases to P_2 at a time t_2 . The effect of discharge

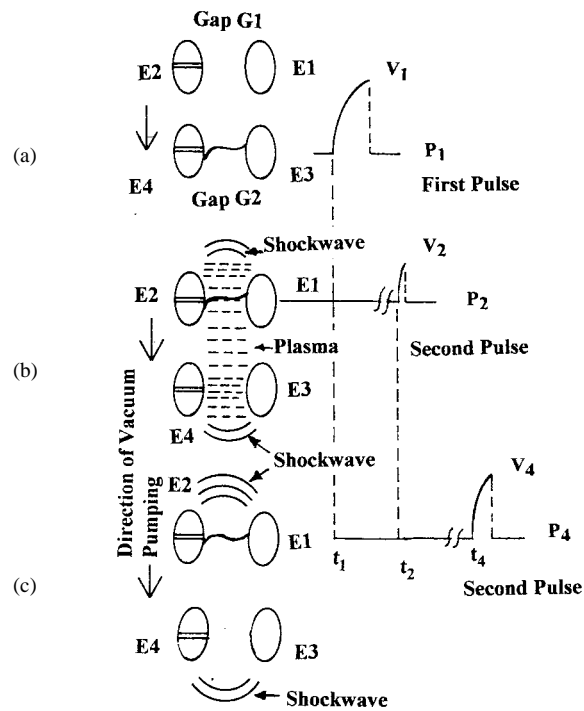


Fig. 4. Breakdown and plasma movement processes in low pressure spark-gap with two sparkgaps, diffusion against the direction of pumping.

in G_2 on G_1 are similar to the case mentioned above but the shockwave velocity can be lower due to shockwave and vacuum pumping are in the opposite directions. If the second pulse is applied at this instant t_2 , the gap G_1 breaks down at a voltage $V_2 < V_1$, as shown in Fig. 4(b) (Fig. 3, point B). This shows that the gap G_1 has been affected due to discharge in G_2 and has not returned to its pre-breakdown status up to a time t_2 . If the second pulse is applied at a later instant t_4 , at which time the pressure is $P_4 > P_1$, as shown in Fig. 4(c) (Fig. 3, point D) due to expansion of the plasma in the gap diffusing against the pumping system, it may breakdown at a voltage $V_4 < V_1$. It can be noted from Paschen's characteristics that with pressure $P_4 > P_1$, the breakdown occurs at a voltage $V_4 < V_1$. However with large delay times, the pressure reaches P_1 corresponding to normal self-breakdown voltage. Breakdowns at higher than normal self-breakdown voltages are generally not possible in these cases. Since there are no discharges in the second gap, the changes in self-breakdown voltages are attributed mainly due to changes in the gap pressure due to first pulse discharge corresponding to Paschen's characteristics.

IV. BREAKDOWN VOLTAGE CHARACTERISTICS

The experiments to determine the breakdown voltage characteristics of low pressure sparkgap with two sparkgaps are conducted for four gap spacings with hydrogen gas at 2.1 Pa gap pressure. Fig. 5 presents the typical pairs of BDV pulses of first pulse to gap G_1 and second pulse to gap G_2 . Fig. 6 presents the typical waveforms of the current in the gap G_1 . The Fig. 7 presents the BDV characteristics of the gap G_2 after the breakdown of the gap G_1 for different

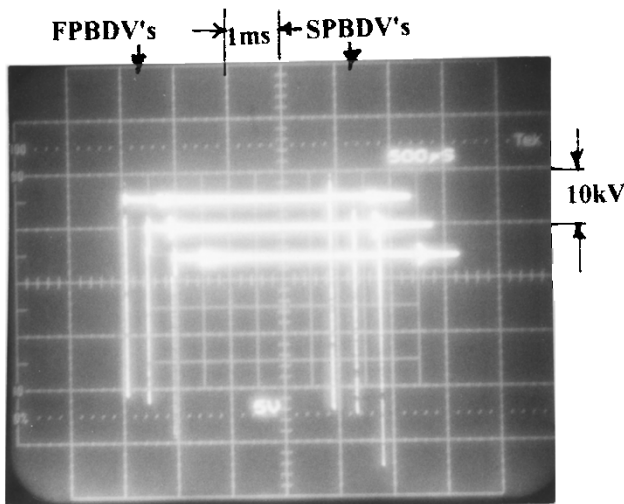


Fig. 5. Typical first and second voltage pulse waveforms, (hydrogen gas, -ve polarity, 10 mm gap, 2.1 Pa, 5.2 Ω).

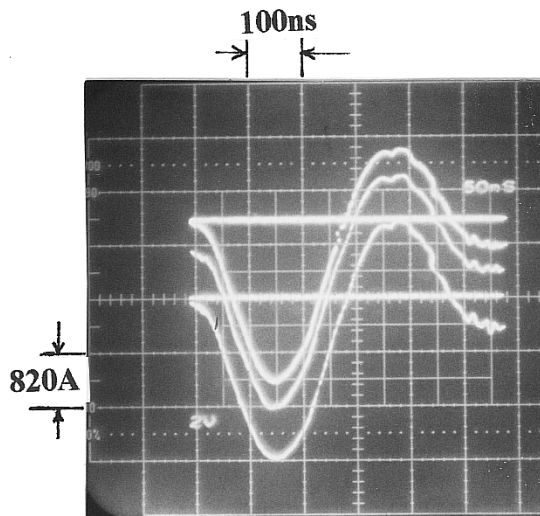


Fig. 6. Typical current pulse waveforms, hydrogen gas, -ve polarity, 10 mm gap, 2.1 Pa, 5.2 Ω , 50% current reversal.

gap spacings. The Fig. 8 presents the BDV characteristics of the gap G_1 after the breakdown of the gap G_2 and vice-versa for 10 mm gap spacings. Each of the characteristics of Figs. 7 and 8 are the average of four similar characteristics. The self BDV's of the gaps [G_1/G_2] have been recorded at regular intervals during the BDV characteristics experiments which are plotted in these characteristics. The recordings show breakdown voltages of the second gap higher than the first gap of the low pressure sparkgap with two sparkgaps. Figs. 9 and 10 shows the recovery characteristics of the two sparkgaps along with spread in breakdown voltage data, after the first pulse breakdown. These characteristics show *over recovery* for both sparkgaps in the range of 25–30%. It may also be noted that the breakdown voltages in these experiments are low compared to two gap experiments due to higher load capacitance (4000 pF against 2000 pF for two gaps). In case of two sparkgaps, two cables discharge through the sparkgap. In case of recovery experiments of single gap, the

four cables discharge into the sparkgap. This changes the risetime of the applied pulse as well as current waveshape. These characteristics for a single low pressure sparkgap have been presented and discussed in [2].

There are mainly two types of breakdown voltage characteristics in case of two sparkgap setup. In *case one*, the first pulse is applied to gap G_1 and in *case two*, the first pulse is applied to gap G_2 . The BDV's of gaps G_1 and G_2 have been reduced due to discharge in the gaps G_2 and G_1 , respectively. Initially the second gap G_2/G_1 breaks down after about 2 to 10 μs of the breakdown of the first gap G_1/G_2 . Once the main discharge is complete, the BDV of second gap G_2/G_1 improves with time, increases from 20 to 80% of its predischage BDV in 200 to 700 μs for *case one* and 27 to 47% for *case two*. It reaches prebreakdown conditions in about 1–3 ms time for *case one*. The BDV of gap G_2 with long gap spacings (6.5 mm and 10 mm) increases to greater than its predischage BDV in less than 10 ms. But the BDV of short gap G_2 (3.5 mm) does not reach its predischage BDV even up to 10 ms. It may be noted that each gap recovery characteristics shows *over recovery* when tested independently (Figs. 9 and 10).

V. DISCUSSIONS

In case of low pressure sparkgap with two sparkgaps, there is a small difference in self BDV of these two gaps due to statistical variations. However, it is not significant. The BDV of gaps G_2/G_1 reduces approximately to zero voltage in less than 5 μs –10 μs (Figs. 7 and 8) due to fast diffusion of plasma at a velocity of approximately 1–2 $\text{cms}/\mu\text{s}$ from gaps G_1/G_2 , respectively. The BDV of the gaps G_2/G_1 improves slowly with time due to diffusion of ions to the walls. It increases to about 1 kV in 25 μs in *case one* (Fig. 7) and about 2 kV in 25 to 60 μs in *case two* (Fig. 8). This shows that majority of the ionizations have moved to the gap G_2 in 25 μs with an average velocity of $\sim 6 \text{ cms}/25 \mu\text{s} = 0.24 \text{ cms}/\mu\text{s}$ for *case one* and to the gap G_1 in 60 μs with an average velocity of $\sim 6 \text{ cms}/60 \mu\text{s} = 0.10 \text{ cms}/\mu\text{s}$ for *case two* due to shockwave by this time. Once the ionization from first gap diffusing to the second gap decrease to zero, the second gap returns to normal at a faster rate. The BDV's of G_2 after the discharge in gap G_1 are higher than self BDV of the gap G_2 for gap spacings of 10 mm, 6.5 mm, and 5 mm, and lower for 3.5 mm for *case one*. The BDV of gap G_1 does not increase to greater than or equal to its predischage BDV for case two. This indicates that the pressure in the gap G_1 does not reduce to below its normal pressure due to slow moving shockwave. Since there is no previous discharge in the gaps G_2/G_1 , change in BDV to greater than its self-breakdown value is possible only with reduction of pressure in the first gap due to discharge in the second gap. This indicates that the pressure in the gap G_2 reduces below normal pressure due to the discharge in the gap G_1 , for 5 mm, 6.5 mm, and 10 mm gap spacings. The shockwave of the gap G_1 may completely enter the larger gap spacings of G_2 and reduce the pressure in the gap to below normal gap pressure. The shock wave may not enter to the gap G_2 without being deflected by the electrodes in case of 3.5 mm gap spacings. The increase in BDV's of 6.5 mm and

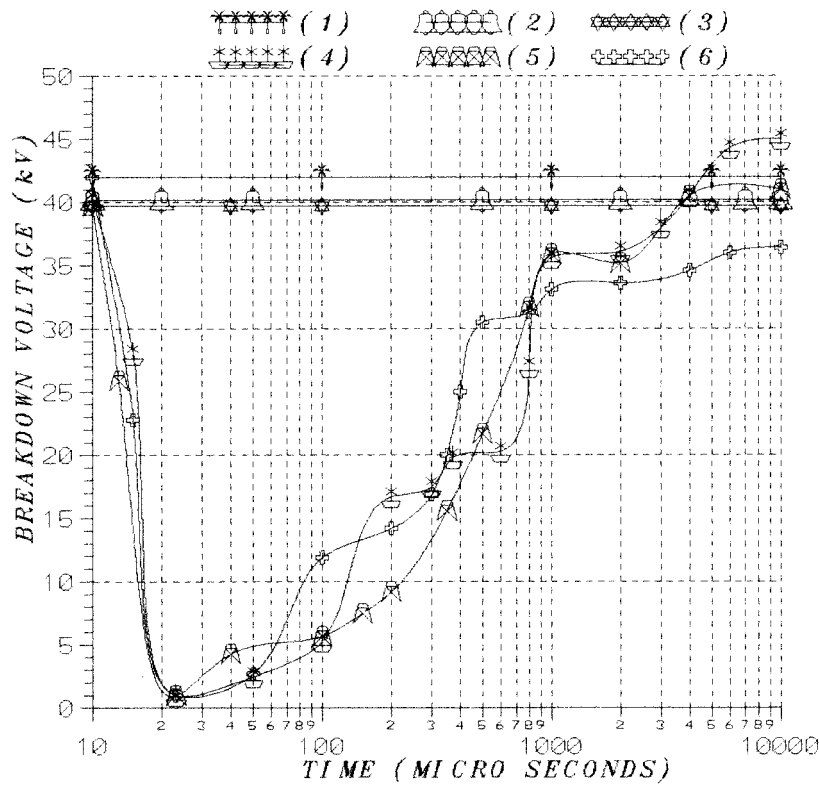


Fig. 7. Second pulse BDV characteristics, hydrogen gas, -ve polarity, 50% reversal (1) SBV of $G_2 = 42$ kV, (2) SBV of $G_2 = 40$ kV, (3) SBV of $G_2 = 39$ kV, (4) $G_1 = 5$ mm, $G_2 = 6.5$ mm, (5) $G_1 = 5$ mm, $G_2 = 5$ mm, and (6) $G_1 = 5$ mm and $G_2 = 3.5$ mm.

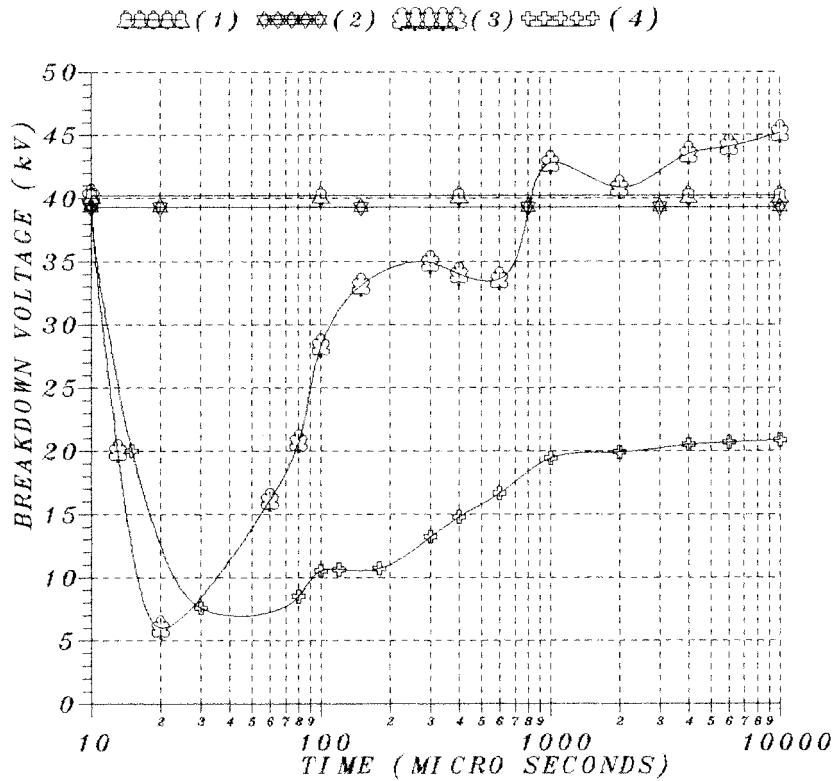


Fig. 8. Second pulse BDV characteristics, hydrogen gas, -ve polarity, 50% reversal (1) SBV of $G_2 = 40$ kV, (2) SBV of $G_1 = 39$ kV, (3) first pulse to G_1 , and (4) first pulse to G_2 .

10 mm gap spacings to greater than their self BDV's clearly demonstrates that the pressure in the gap reduces to lower

than its normal pressure, since there is no previous discharge in this gap. This also indicates that the probability of change in

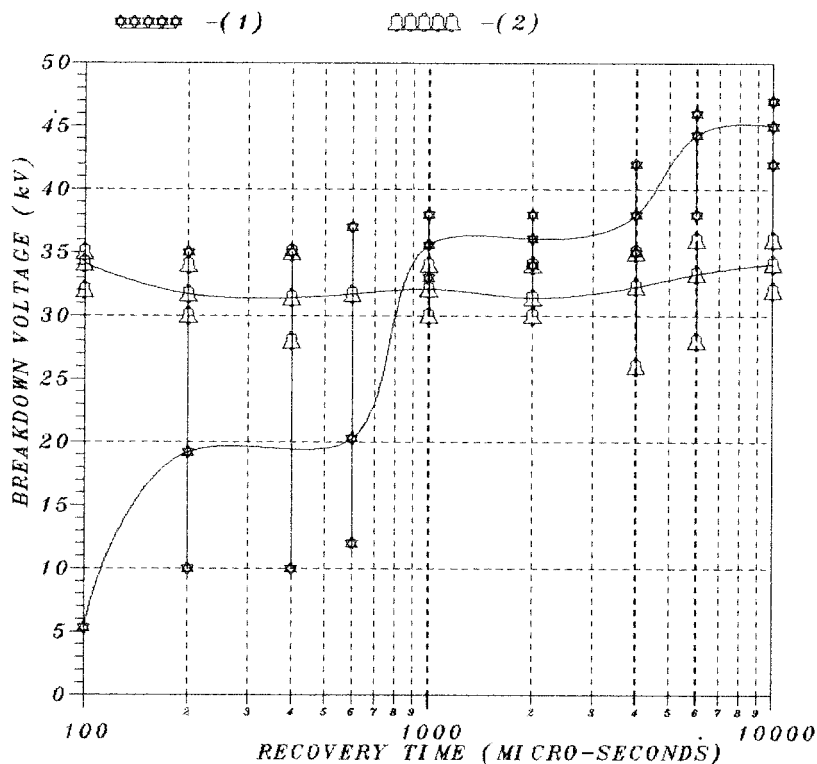


Fig. 9. Significance of over recovery with range of breakdown voltages of first gap for hydrogen gas, 5 mm gap, -ve polarity, 50% current reversal, 5.2 Ω load, 2.1 Pa pressure: (1) recovery pulse BDV's and (2) first pulse BDV's.

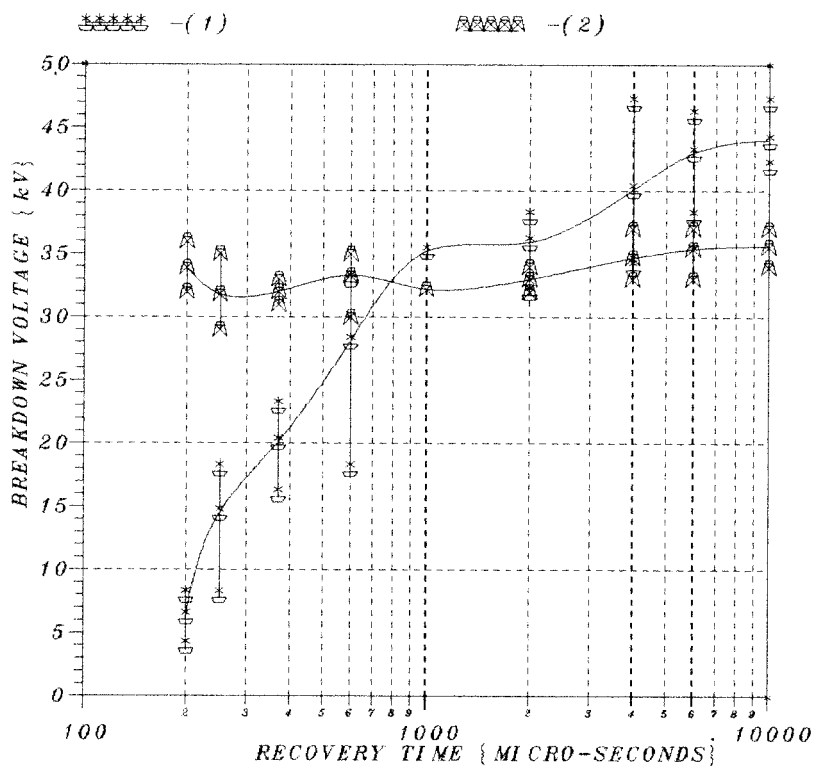


Fig. 10. Significance of over recovery with range of breakdown voltages of second gap for hydrogen gas, 5 mm gap, -ve polarity, 50% current reversal, 5.2 Ω load, 2.1 Pa gap pressure: (1) recovery pulse BDV's and (2) first pulse BDV's.

BDV to greater than its self-BDV value in one sparkgap due to the discharge in the other is very high when the shockwave has to move in the direction of pumping system. The pressure

reduction in the gap below normal pressure after discharge is the main reason for *over recovery* of the low pressure sparkgaps to the left of Paschen's minimum.

VI. CONCLUSIONS

The discharge in one of the gaps reduces the BDV of the other gap placed some distant apart in a two gap setup. This change is a function of shockwave velocity and direction of pumping. This can lead to changes in BDV's, greater than its predischage BDV of the other gap. The change in BDV's is less predominant in gaps greater than or equal to the first gap. The *over recovery* of the low pressure sparkgaps can result when the shock wave produced due to first pulse discharge can reduce the pressure in the same gap to below normal pressures. Even though the experiments have been conducted for only hydrogen gas, similar behavior can be expected from other gases like argon, deuterium, etc.

ACKNOWLEDGMENT

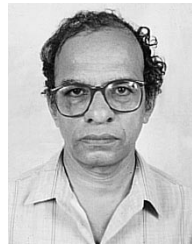
The authors are thankful to staff members of Accelerator and Pulse Power Division for useful discussions and support. They would also like to thank Dr. S. S Kapoor, Director, Physics and E & I Groups, BARC, for his keen interest and encouragement.

REFERENCES

- [1] K. V. Nagesh, "A study of recovery times of low pressure sparkgaps," Ph.D. dissertation, Indian Inst. Sci., Bangalore, India, July 1997.
- [2] K. V. Nagesh, P. H. Ron, G. R. Nagabhushana, & R. S. Nema, "Over recovery in low pressure sparkgaps," *IEEE Trans. Plasma Sci.*, vol. 27, pp. 199–210, Feb. 1999.
- [3] H. Hermansdorfer, "Microwave diagnostics techniques," in *Plasma Diagnostics*, W. Lochte-Holtgreven, Ed. Amsterdam, The Netherlands: North Holland, 1968, p. 478, ch. 8.

- [4] S. M. Turnbull, S. T. Macgregor, F. A. Tuema, and O. Farish, "A quantitative laser Schlieren method for measurement of neutral gas density in high pressure gas switches," *Meas. Sci. Technol.*, vol. 4, pp. 1154–1159, 1993.
- [5] G. A. Mesyats and D. I. Proskurovsky, *Pulsed Electrical Discharges in Vacuum*. New York: Springer-Verlag, July 1988, ch. 4.53,
- [6] K. Tsuruta and H. Ebara, "Modeling of a gas temperature decay after arc discharge in small air gaps," *IEEE Trans. Dielect. Elect. Insul.*, vol. 27, pp. 451–456, June 1992.

K. V. Nagesh, for a photograph and biography, see p. 210 of the February 1999 issue of this TRANSACTIONS.



P. H. Ron received the B.E. degree from Poona University, India, in 1961, the M.Sc.(Engg.) degree from the University of Manchester Institute of Technology, Manchester, U.K., in 1969, and Ph.D degree from the Indian Institute of Science, Bangalore, India, in 1984.

He was a Visiting Scientist at the National Research Council, Ottawa, Ont., Canada, in 1985 and McGill University, Montreal, P.Q., Canada, in 1987. He has been working in the fields of high voltage insulation engineering, multigigawatt pulse power systems, pulsed high magnetic fields, EMI/EMC, and industrial electron accelerators.

R. S. Nema, for a photograph and biography, see p. 210 of the February 1999 issue of this TRANSACTIONS.