ISDEIV 2008 ASN 104 Bucharest Romania

Studies in Inverse Magnetron Discharges of Vacuum Interrupters: Part 1 – Variations in Electric Field

L.T. Falkingham[1], R. Reeves[1], C. H. Gill[1] and S. Mistry[1]

[1]Vacuum Interrupters Ltd, Sir Frank Whittle Business Centre, Great Central Way, Rugby CV21 3XH, UK

***Abstract*- This paper reports part of a series of experiments to provide detailed information on the characteristics of inverse magnetron discharges in vacuum interrupters. This technique is used widely in the manufacture of commercial vacuum interrupters to determine the level of vacuum and predict the service life. The variation of discharge waveforms with applied voltage were examined for both single and double inverse magnetron discharges.**

I. Introduction

The paper describes part of a study of inverse magnetron discharges in vacuum interrupters. This type of discharge is widely used to measure the vacuum in vacuum interrupters during the production process. Vacuum interrupters are sealed for life devices and in order to estimate the vacuum life of each vacuum interrupter most manufacturers use a measure of the vacuum pressure to estimate the apparent leak rate. This is usually done using a Penning discharge or an inverse magnetron discharge [1].

Single Inverse Magnetron Discharge (SIM)

In an inverse magnetron discharge an electric field and a magnetic field are applied to the vacuum space at right angles to each other [2]. In the single inverse magnetron mode the interrupter contacts are closed, the interrupter is placed in a solenoid which provides an axial field, and a high dc voltage is applied between the contacts and the centre shield, setting up a radial electric field, fig. 1.

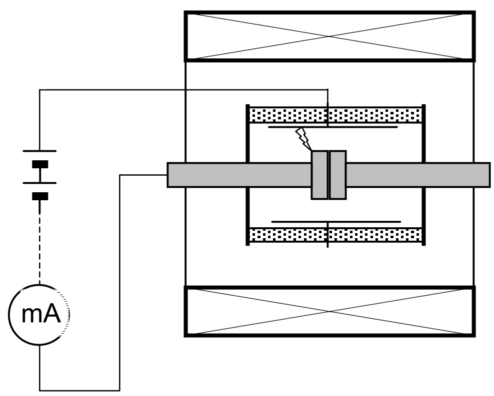


Fig. 1: Vacuum interrupter in Magnetron coil connected for Single Inverse Magnetron mode.

Without the magnetic field no current would flow, due to the very low gas pressure, but the magnetic field causes electrons and ions to travel in circular paths, greatly increasing the number of ionising collisions occurring, and in theory giving an ability to measure pressures down to 10^{-10} mbar [3]. When the fields are switched on there is a discharge resulting in a small pulse of current: gas in the interrupter is ionised and transported to the electrodes providing the electric field. This pulse is recorded and as the pulse height is proportional to the amount of gas in the vacuum space, this gives a measurement of pressure (Figure 2).

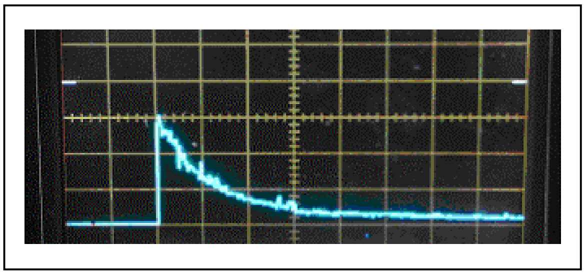


Fig. 2: Typical current pulse for a single inverse magnetron discharge.

Double Inverse Magnetron Discharge (DIM)

If the centre shield cannot be electrically connected from outside, then the double magnetron mode must be used. For this the contacts are opened and the voltage is connected across the two contacts: the centre shield is of floating potential and charges capacitively. A radial electric field becomes established between one contact and the centre shield, and a second radial electric field becomes established between the centre shield and the second contact. Thus the current path consists of two discharges in series, Fig. 3.

Of course an interrupter whose centre shield is accessible from outside can be tested by both the single and the double magnetron method.

We examined the features of the discharges for single and double inverse magnetron events, and noted how they were affected by variations in the applied voltage with a fixed magnetic field. The key features investigated were the height of the pulse, the shape of the pulse, and high frequency noise sometimes found to be superimposed on the pulse.

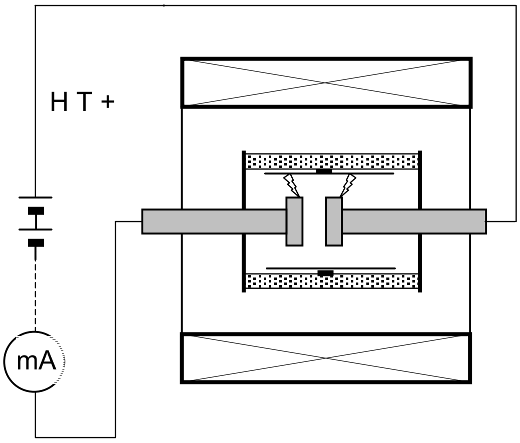


Figure 3: Vacuum interrupter in Magnetron coil connected for Double Inverse Magnetron mode.

II. The Experimental Setup

Equipment

The solenoid used 40 kg of copper wire on a former 180mm long and with a central hole of diameter 250mm (Fig. 4). This allowed the largest interrupters we are aware of to be tested. The coil is of optimised geometry and is powered from a 2kW dc current supply, giving a maximum field of 700 Gauss.

Figure 4: A vacuum interrupter in position in the solenoid coil.

The high voltage supply provides up to 10kV dc, and has a current capacity of 10mA.

The pressure measured is proportional to the height of the current pulse which may vary from about 2μA to 5mA. The captured pulse is displayed on a digital storage oscilloscope, fig. 2. Since we can expect one day to have a failed interrupter under test, it has to be assumed that the full 10kV could be input to the data capture electronics, and precautions are taken to mitigate the effects of this.

The Experimental Method

The interrupters were selected to have sufficient "permanent" gases (explained later) so that they did not pump significantly during the series of experiments. Thus after an initial pumping effect the pressure became stable and was therefore suitable for our experiments.

The interrupter we used for these tests was a V8 type, manufactured by VIL, which had been in service use for about 25 years. We obtained similar results when we tested a second V8 interrupter.

In Part 1, described here, we kept the magnetic field fixed at 700 Gauss, and varied the applied voltage from 10kV to 0.5kV. In Part 2, described elsewhere, we kept the applied voltage fixed at 4kV and varied the magnetic field from 700 Gauss to 100 Gauss.

Pulse Initiation

Often the pulse occurs as soon as the fields are applied, but sometimes there may be a delay of a few seconds, and occasionally a delay of up to a minute before a discharge is observed. This delay appears to be longer with higher vacuum levels. We believe that when there is a good vacuum it is necessary for some event such as the arrival of a particle of natural radiation to provide the first ionisation event. It is sometimes the case that no discharge at all occurs even after waiting for up to a minute. We interpret this as meaning that there is such a good vacuum, of the order of 10^{-7}mbar, that it is very difficult to strike the discharge.

III. Experimental Results

A summary of the main results is shown in Fig. 6. The voltages were changed from high to low and then from low to high in steps, twice over, giving four readings at each voltage.

The General Form of the Pulses

The first pulse obtained from this interrupter is shown in Fig. 5 and has several features. Firstly there is a very rapid rise of current, lasting about 200 μs. Next there is a decay of the current to a steady level, which is in two parts. First there is a fast fall to an inflexion point then an exponential decay, with a time constant of about 300 ms. Finally there is a steady discharge tail which continues until we switch the high voltage off.

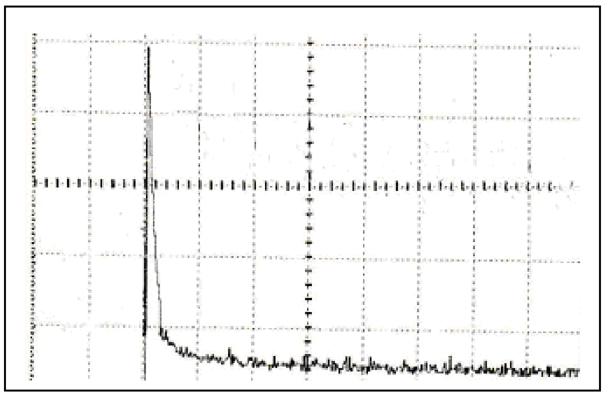
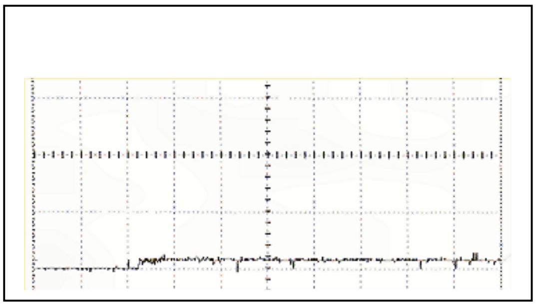
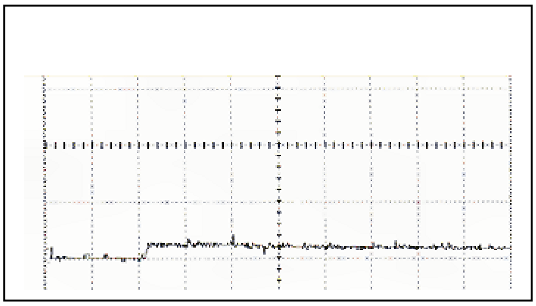


Fig. 5. Typical first inverse magnetron discharge pulse.

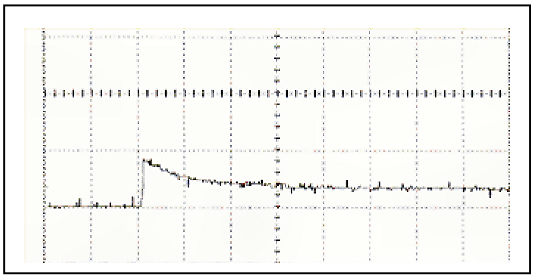
10kV SIM



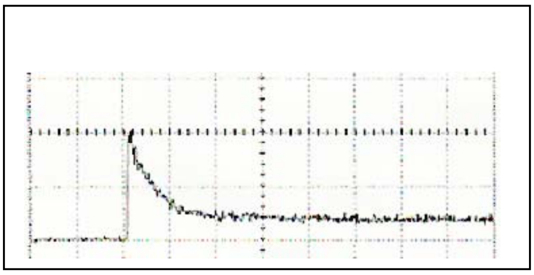
7.5kV SIM



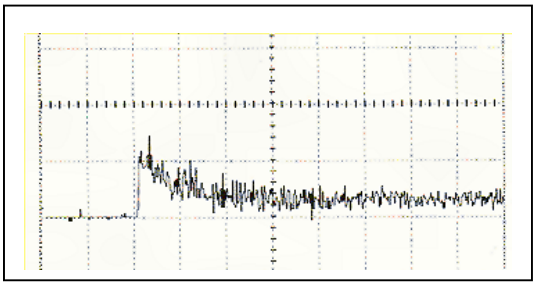
5kV SIM



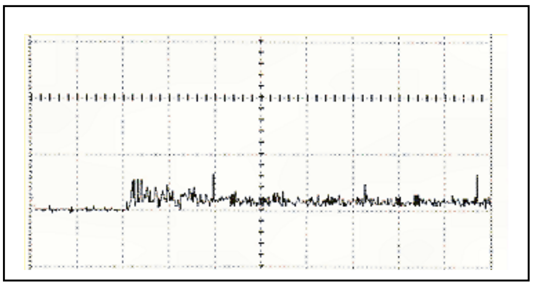
2.5kV SIM



2.0kV SIM

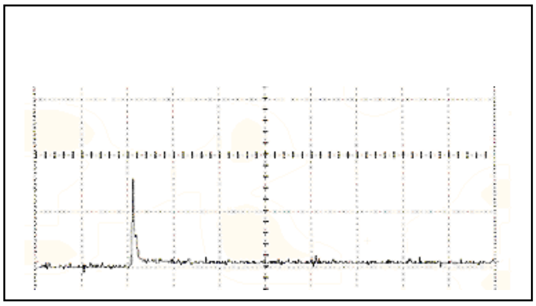


1.0kV SIM

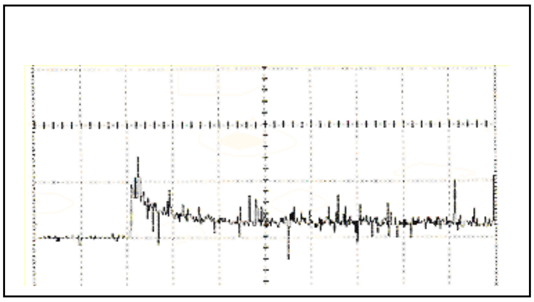


0.5kV SIM – We found no discharge below 0.8kV

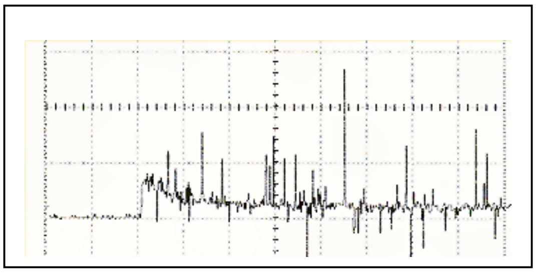
10kV DIM



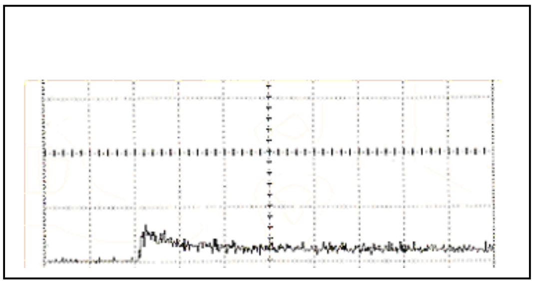
7.5kV DIM



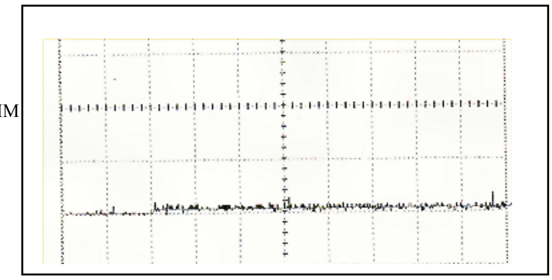
5kV DIM



2.5kV DIM



2.0kV DIM



1.0kV DIM – we found no discharge below 2.0kV.

Figure 6. Series of oscillographs showing evolution of discharge with applied voltage, for one of the interrupters tested. The series on the left shows Single Inverse Magnetron (SIM) and the series on the right shows Double Inverse Magnetron (DIM) discharges. The vertical scale is 2μA/division and the horizontal scale is 200mS/division.

If the test is repeated several times for one interrupter, we find that the second and subsequent pulses are lower than the first pulse because they do not have the rapid decay part, only the exponential decay (Fig. 2). The "pumping effect" seen with the first test is well known. We believe that the pumping takes place during the fast fall period and is due to there being what we term "permanent" and "impermanent" gases in the vacuum. Permanent gases are inert gases or not very reactive gases, which after reaching the electrodes as ions and having their charges neutralised are free to return to the gas state. Impermanent gases are destructible; they may for example be organic molecules which are broken down by the discharge into carbon, hydrogen, and reactive radicals that can become permanently bonded to the very clean metal parts inside the interrupter, and inert or less reactive gases that survive as permanent gases.

We interpret the exponential falling off of the current once the pumping effect is complete as being due to ions becoming electrostatically bonded to the electrodes at least for a period. We interpret the final steady current as being due to a steady state balance of gas molecules being neutralised and drifting off the electrodes, against those becoming ionised again.

The signals all exhibit some noise, which is probably due to irregular flow of the discharge current. The noise is relatively large for small pulses, and can make the pulse height difficult to estimate to within better than ±20 percent. However this is still acceptable for pressure measurement as vacuum is measured on a logarithmic scale.

Variation of Pulses with Voltage

The applied voltage was varied from 0.5kV to 10kV for both SIM and DIM discharges on the same interrupter. Several measurements were made at each voltage and the results were consistent. A sample of the results is shown in Fig. 6. All oscillogrammes shown in this paper are to the same scale with the exception of Figure 7.

IV. Discussion

SIM Discharge.

There appear to be two phenomena. Above 2 kV the discharge is relatively free of noise and decreases in amplitude with increasing voltage.

At 2kV and below the discharge is much more noisy and the peak amplitude decreases with decreasing voltage. On an expanded timebase the noise can be seen to exhibit a distinctive sawtooth waveform (Fig. 7: 1.0kV SIM discharge). We believe that this indicates that the voltage is insufficient to maintain the discharge continuously. This behaviour continues until the magnetic field is switched off. We noted that the period of the sawtooth decreased as the voltage rose, and the amplitude declined slightly.

Below 0.8 kV no SIM discharge was obtained.

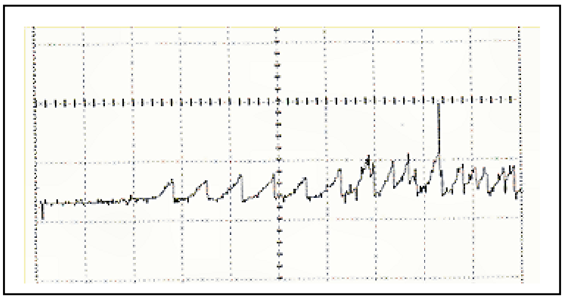


Fig. 7: SIM waveform at 1kV. The current scale and the timebase are expanded by 10x compared to those in Fig. 6.

DIM Discharge

There appear to be three phenomena;

Above 7.5kV we see a sharp initial pulse with very little steady tail.

Between 2.5kV and 7.5kV we see a clear initial pulse and tail, with multiple high frequency spikes. This seems to be a feature of the double magnetron situation. The height of the pulse increases with increasing voltage in this range.

Below 2.5 kV the pulse reduces with voltage and has the same sawtooth waveform as in Fig. 8.

Below 2.0kV no DIM discharge was obtained.

Comparison of SIM and DIM Discharges

The amplitudes of the SIM and DIM pulses were similar at 5 kV. At higher voltages the DIM pulses were higher than SIM pulses and at lower voltages the SIM pulses were higher than DIM pulses.

The SIM mode and the DIM mode give different peak currents for the same vacuum level. The difference can be of the order of two or three times. This is significant enough, even on a logarithmic scale, that when the magnetron method is used to measure pressure during the manufacture of vacuum interrupters, it is necessary to calibrate the equipment separately for each type of discharge.

V. Further Work

We intend to continue these investigations to try to understand the high frequency spikes seen in the DIM mode, and to establish the reasons for the difference in trend in peak current between SIM mode and DIM mode discharges. We will also investigate whether the original sharp peak seen on the first discharge reappears after a long delay, or whether the impermanent gases have indeed been permanently removed from the vacuum.

In Part 2 of these studies we will study the effect of varying the magnetic field with a fixed electric field.

VI. References

[1] Falkingham L. T. "The Assessment of Vacuum Insulation Condition in Time Expired (>20 Years Old) Vacuum Interrupters and Switches" *10th Insucon International Conference Birmingham (2006)*

[2] Penning F. M. & Nienhuis K. *Philips Technical Review No. 11, p116, (1949)*

[3] Weston G. F. *Ultrahigh Vacuum Practice* Butterworths, (1985).

E-mail of authors: reeves@vil.org.uk