Studies in Inverse Magnetron Discharges of Vacuum Interrupters: Part 2 – Variations in Magnetic Field

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***Abstract-* This paper reports the second 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 magnetic field was examined for both single and double inverse magnetron discharges.**

I. INTRODUCTION

The paper reports the second 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 manufacture, and can also be used to check the vacuum after many years of service use.

Part 1 of the study was published previously [1] and examined the variation in current pulse as the applied voltage was varied in a fixed magnetic field. This part of the study examines the variation in current pulse as the magnetic field is varied with a fixed applied voltage.

We described the detailed operation of the single inverse magnetron (SIM) discharge and the double inverse magnetron (DIM) discharge in the previous paper. A simple explanation is that the inverse magnetron discharge occurs when an electric field and a magnetic field are applied to the vacuum space at right angles to each other [2]. A SIM discharge occurs when the electrical connections are made to the closed contacts and to the centre shield of a vacuum interrupter (VI) as shown in fig 1.

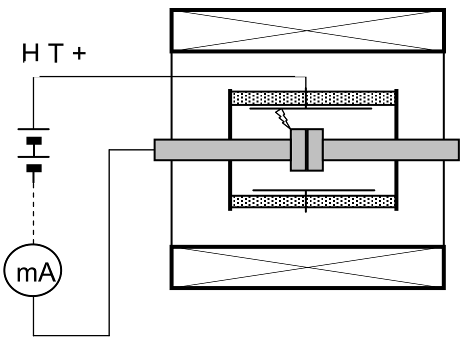

Fig. 1: Vacuum interrupter in Magnetron coil connected for single inverse magnetron (SIM) mode.

A DIM discharge occurs when the voltage is connected across the two contacts of a VI with the contacts open: the centre shield is at floating potential and charges capacitatively. 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.

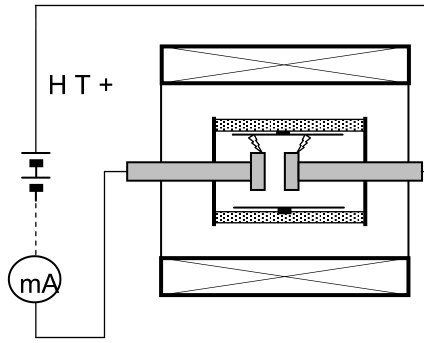

Figure 2: Vacuum interrupter in Magnetron coil connected for Double Inverse Magnetron mode.

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 (Fig. 2).

We examined the features of the discharges for single and double inverse magnetron events, and noted how they were affected by variations in the magnetic field

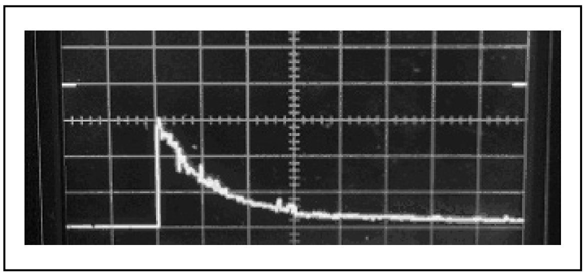

Fig. 3: Typical current pulse for a double inverse magnetron (DIM) discharge.

with a fixed applied voltage. The key features investigated were the height of the pulse, the shape of the pulse, and high frequency noise often found to be present in the pulse.

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II. THE EXPERIMENTAL SETUP

A. 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: An 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 according to the degree of vacuum. The pulse is captured on a digital storage oscilloscope, fig. 2.

B. The Experimental Method

In Part 1, previously reported, we kept the magnetic field fixed at 700 Gauss, and varied the applied voltage from 10kV to 0.5kV. In Part 2, described here, we kept the applied voltage fixed at 5kV and varied the magnetic field from 650 Gauss down to fields at which no discharge occurred.

The interrupter tested was selected to have sufficient “permanent” gases (explained in Part I) that it did not pump significantly during the series of experiments.

It was a V8 type, manufactured by VIL, which had been in service use for about 30 years. Its vacuum pressure was roughly 3 x 10^{-4} mbar. The contact gap used for DIM was 3.5 mm.

C. Striking of pulses

When a pulse occurs we call this a strike. The voltage was always applied first, and then the magnetic field was turned on. Usually a strike occurred without noticeable delay or after a few seconds of delay. At the lower magnetic fields striking became more difficult. If there was no delay in 30s we recorded this as a “no strike”. We did three tests at each field setting, waiting up to 30s, 30s and 60s for a strike in the first, second and third tests.

III. EXPERIMENTAL RESULTS

A summary of the main results is shown in Fig. 5. Three pulses were obtained at each field setting, only one is shown in the figure. Usually the three pulses in a set were similar but not identical. During the period of the experiment there was no sign of the pressure in the VI changing.

A. Form of the pulses

With the SIM pulses there is a rapid rise in current followed by decay down to a steady non-zero level. Initially there is often considerable noise on the waveform, which reduces after a period to leave a waveform with little more than the background electronic noise (example Fig 5. SIM 600 gauss)

At the higher fields the pulses have the appearance of a simple exponential decay. At very low fields the pulse decays to zero and cuts off sharply (example Fig 5 SIM 350 gauss). We call theses pulses Sail Pulses, because of their appearance. Sail pulses have no noise on them, and are associated with difficulty in striking. Table 1 shows this. At intermediate fields the pulse decays to a low level but then rises up to a steady level. We call these dipped pulses (example Fig 5 SIM 400 gauss).

There is a steady progression from sail pulses through dipped pulses to exponential pulses. Figure 6 shows the SIM pulse for 500 gauss, with the vertical scale expanded. Even at this field it can be seen that it has a small but distinct dip which is not apparent at higher fields.

The DIM pulses are generally smaller than the SIM pulses. At the lower fields they decay slowly after the initial rise and then switch off abruptly. The time elapsed to switch off increases as the field is increased. Again, at the lower fields there is difficulty with striking, shown in Table 1. In this region some discharges almost quenched and then reignited in an oscillatory manner (Fig 5 DIM 350 gauss).

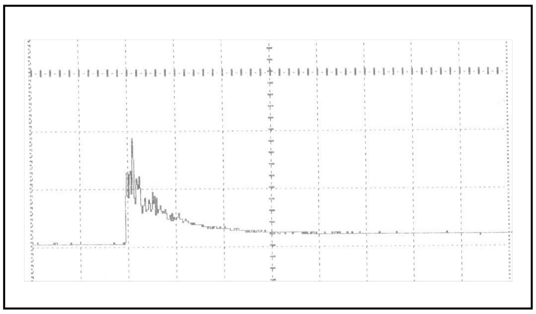
B. Consistency of the pulses

Generally the sets of three pulses taken for each data point were very similar except that the noise component varied.

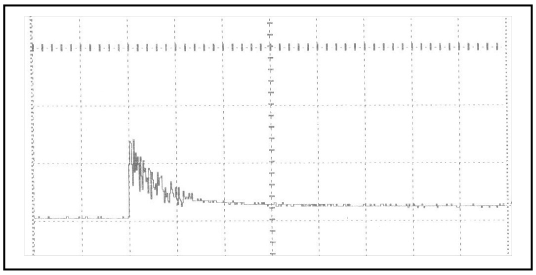
C. Consistency of pulse heights

Pulse heights were measured from the oscilloscope traces. Because of the noise on all pulses there is some difficulty in estimating the true peak value of a pulse, both in deciding where the peak is and in estimating its

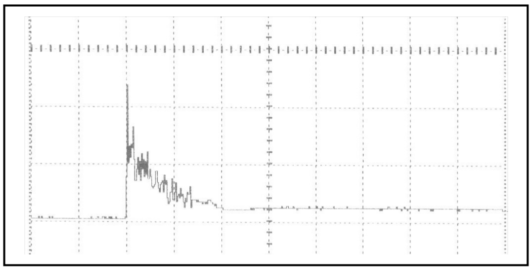
650 gauss
SIM



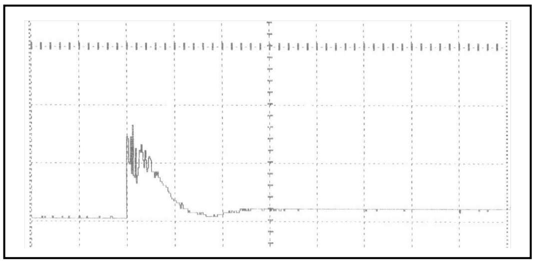
600 gauss
SIM



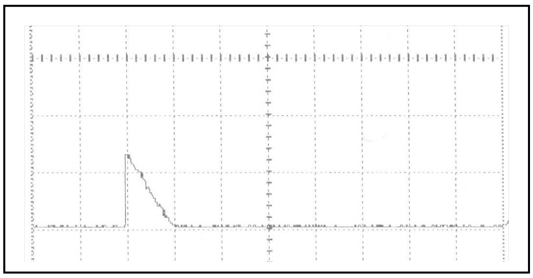
500 gauss
SIM



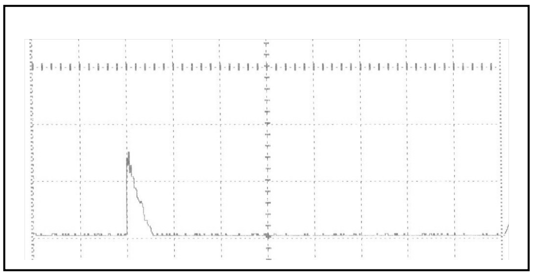
400 gauss
SIM



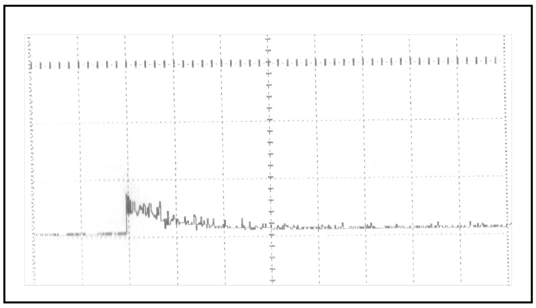
350 gauss
SIM



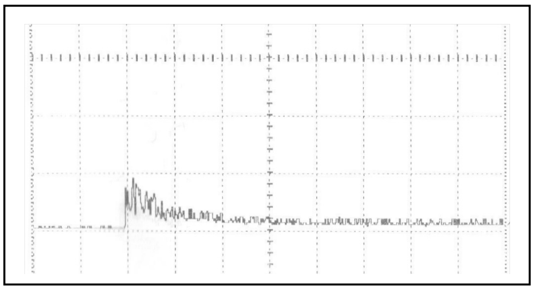
300 gauss
SIM



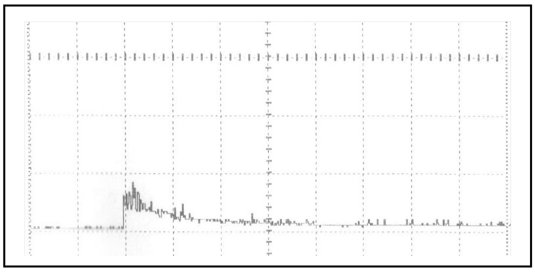
650 gauss
DIM



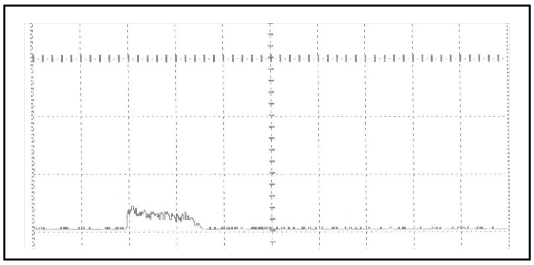
600 gauss
DIM



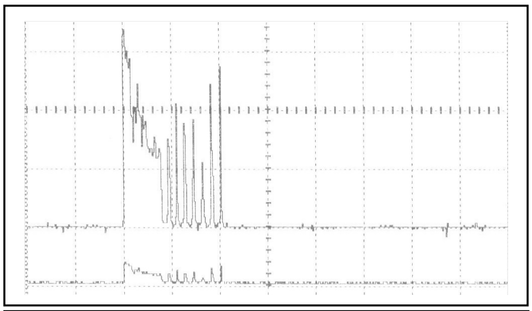
500 gauss
DIM



400 gauss
DIM



350 gauss
DIM



300 gauss
DIM

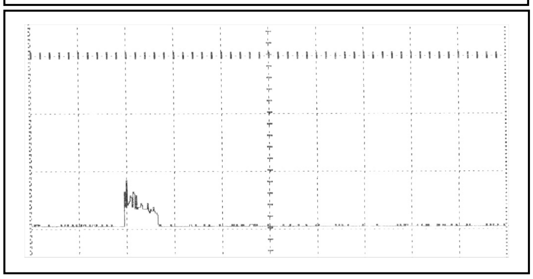


Figure 5 (previous page). Series of oscillographs showing evolution of discharge with applied voltage, for one of the interrupters tested. The series on the left shows Single Inverse Magnetron (SIM) and the series on the right shows Double Inverse Magnetron (DIM) discharges. The vertical scale is 2µA/division and the horizontal scale is 200mS/division The 350gauss DIM chart shows the normal pulse below and the same pulse expanded by 10 times to show the detail.

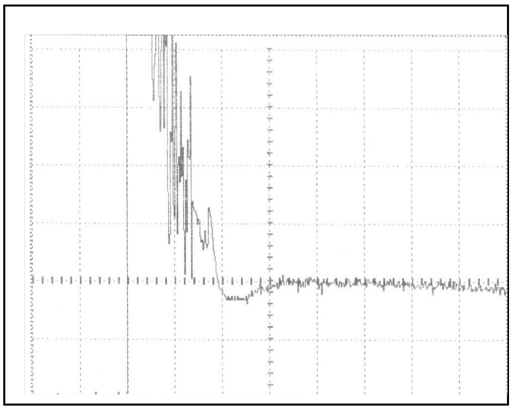


Figure 6. The SIM pulse for 500 gauss with an expanded vertical scale.

TABLE 1. VARIABILITY OF PULSE HEIGHTS

	Pulse heights, µA		
Magnetic field, gauss	*First test*	*Second test*	*Third test*
Single inverse magnetron			
300	no strike	no strike	280
350	180	no strike	no strike
400	280	260	260
500	480	300	400
600	280	280	430
650	260	260	320
Double inverse magnetron			
300	no strike	no strike	80
350	no strike	70	no strike
400	70	150	no strike
500	120	120	110
600	130	140	150
650	140	140	160

value. Generally the peak was assumed to be in the centre of the noise signal. As the peak-to-peak amplitude of the noise was about half of the pulse heights, there is roughly a 25% uncertainty in estimating the pulse height. As the pressure is on a logarithmic scale this is considered acceptable.

The pulse heights obtained from the three tests made at each magnetic field setting are shown in table 1.

It can be seen that there is no marked variation of pulse heights within the data, which means that despite the variation of pulse form with field, within the noise limitation the initial pulse heights are constant and the field value does not much affect the measured value of vacuum pressure. This applies to both SIM and DIM measurements.

D. Comparison of SIM and DIM Discharges

The average pulse height in Table 1 for SIM pulses is 305µA, and for DIM it is 131µA. (Non-strike pulses are not included). Thus the DIM pulses are roughly half the height of the DIM pulses. Because of the high level of noise on the signals, the error in these means must be of the order of 20%. One point of interest is that pulses at fields of below 400 gauss were half the height of those above 400 gauss which may indicate a step change in the peak value. We obtained the same pattern of results when we tested two other V8 interrupters.

IV. DISCUSSION

It is clear that the pressure measurements using the pulse peak value were highly repeatable and not much affected by pulse shape. The results presented here apply to one particular example of one design of interrupter, the VIL V8, at one particular pressure, however identical tests were also carried out on a number of VI of the same design and age, with similar results. Overall the results show that both the SIM and DIM discharge peak values are extremely repeatable over a wide range of magnetic fields. Also within a certain range the value of the magnetic field had no influence on the value of peak discharge current. When taken in conjunction with the results from part 1 of our experiment where the applied voltage was varied, there is a strong indication that for a given vacuum level peak discharge current value is very consistent within a wide range of the applied magnetic field and the applied voltage. This is despite indications that the discharge itself changes, as indicated by the "smooth" and "noisy" pulse forms.

For DIM at 350 gauss we saw the discharge pulsing on and almost off, and at 300 gauss the discharge quenched after a short time. Below 300 gauss there were no discharges.

V. FURTHER WORK

The change in peak pulse value for the DIM tests with magnetic fields of less than 400 gauss is of interest, and may indicate a change in the discharge, which is surprisingly consistent for the higher fields. We shall perform further work to investigate this and to see if it is a real effect and if it occurs sharply or there is a "change-over" zone.

REFERENCES

[1] L. T. Falkingham R. Reeves C. H Gill. S. Mistry "Studies in Inverse Magnetron Discharges of Vacuum Interrupters: Part I – Variations in Electric Field", *ISDEIV, Bucharest, Romania (2008)*

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