Studies in Inverse Magnetron Discharges of Vacuum Interrupters – Part 3 - Anomalies

L.T. Falkingham, R. Reeves, S. Mistry
Vacuum Interrupters Limited, Sir Frank Whittle Business Centre,
Great Central Way, Rugby, CV21 3XH, UK

***Abstract*- This is the third part of a series of investigations into inverse magnetron discharges in vacuum interrupters. In the previous papers the effect of variations in the magnetic and electric fields were studied. A number of anomalies in the discharge waveforms were seen, including what appeared to be step changes in the characteristics. Different anomalies occurred for single and double magnetron discharges. In this paper we examine the anomalous effects more deeply. We examined only the Single Inverse Magnetron (SIM) discharge, and not the Double Inverse Magnetron type. specifically the Pressure-Voltage relationship for a fixed magnetic field, where we see that the relationship reverses at a particular voltage, and also the Arc Stability-Magnetic Field relationship for a fixed voltage, where the arc characteristic changes from smooth to noisy, and there is a distinct change in the waveform shape. We determined that the reversal of the Pressure- Voltage relationship is real and occurs over a small range of voltage. However we have not been able to explain this. For the Arc Stability-Magnetic Field relationship, we determined that this is also a real effect, and believe that it comprises of two distinct discharges, a smooth discharge that occurs for all values of magnetic field and a noisy discharge that occurs and increases once the magnetic field reaches a critical value. We believe that this may be due to local outgassing of the electrodes commencing which causes a secondary discharge involving these evolved gasses.**

I. INTRODUCTION

The paper describes the third part of a detailed study of inverse magnetron discharges in vacuum interrupters [1] [2]. The inverse magnetron discharge is widely used to measure the level of vacuum in vacuum interrupters (VI) during the production process, and to assess their expected vacuum life [3]. Vacuum interrupters are sealed-for-life devices, and manufacturers almost universally use a measure of the vacuum pressure to estimate the apparent leak rate for each device. This is usually done using either an inverse magnetron discharge or alternatively a Penning discharge[4] [5], these techniques have been in existence for many years and give a reliable measure of vacuum which can be calibrated back to basic standards [6].

II. THE EXPERIMENTAL SETUP

A. Equipment

We used the test coil used in the previous experiments which is a single coil containing 40kG of copper, 180mm long and with a hole of 250mm in order to fit the largest interrupters if necessary. It is powered from an Agilent 6574A 2kW dc current supply, which allows the current and therefore the magnetic field to be precisely varied.

The field in the gap for the test coil was measured using an AlphaLab GM-1-ST dc Gaussmeter.

Unfortunately the VI used in the previous experiments were no longer available and so similar VI, but of a different type from the same manufacturer was used. This gave the same phenomena as in the previous case, but the values of magnetic field at which they occurred were now different. We assume that this is due to of differences in internal geometry of the VI. Despite the field value where the effects were seen being now different, the results were effectively the same, and were consistent with this type of VI and fully repeatable.

The results show that minor variations in the magnetic field did not affect the results. We also repeated some of the tests using a second DC HV power supply, which confirmed that the anomalies were not an artifact of the test setup.

B. Experimental technique

After analyzing the previous results we repeated the tests with the new VI using the same parameter values where anomalies had been seen and identified the same anomalies, and then repeated the tests with small variations in field or voltage above and below these values. This was to identify whether the anomalies grew over a range of values or whether there was a sudden change in the effect being seen. We performed each measurement three or six times to assess the consistency of the results.

III. EXPERIMENTAL RESULTS

There were two anomalous effects, previously identified [1] [2], which were studied in this work;

978-1-4673-1265-3/12/$31.00 ©2012 IEEE

A. Pulse waveform v Field Relationship

In our second paper [2] we found that for a fixed applied voltage of 5kV the form of the SIM discharge changes significantly between 350 gauss and 400 Gauss. At 350 Gauss and below the discharge is characterized by a smooth pulse with an almost triangular form and very low noise. At 400 Gauss and above it changes to a noisy discharge with significant high frequency modulation and an asymptotic decay. With the new VI these values of field changed to 400 Gauss and 500 Gauss but otherwise the effect was the same.

B. Peak Current v Voltage Relationship

In our previous work [1] we found that for a SIM discharge the value of peak current at a fixed magnetic field of 700 Gauss increased with increasing voltage up to 2.5kV, however at 5kV and higher the peak value decreased with increasing voltage. This effect was not seen for a DIM discharge where the value of peak current increased with increasing voltage across the range of measurements.

IV. DISCUSSION

The experiments show that firstly both anomalies studied are in fact real effects, and not an artifact of the experimental setup.

A. Pulse Waveform v Field Relationship

The first effect studied was the Pulse Waveform v Field relationship. We previously identified two distinct types of discharge which we called the Asymptotic form and the Sail form. However upon closer examination of the changeover zone we have now found that there is a third type of discharge between the two forms we identified previously, which we have called the ”Hump” waveform. Also, improvements in our instrumentation mean that we were now able to detect very low pulses where previously we thought that there was no discharge, and we now saw a fourth waveform which we have a called “Step”. We believe that these Step discharges were present in our previous work but were not detected at that time. Examples of these four waveforms are shown below;

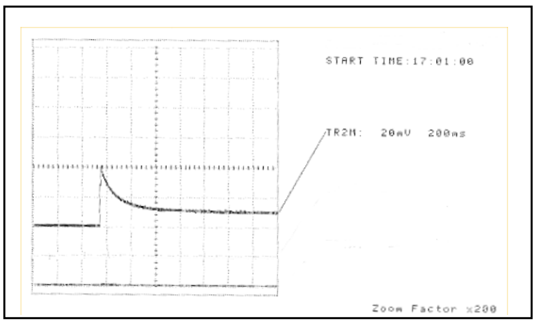

Fig. 2. Figure 1 Asymptotic waveform

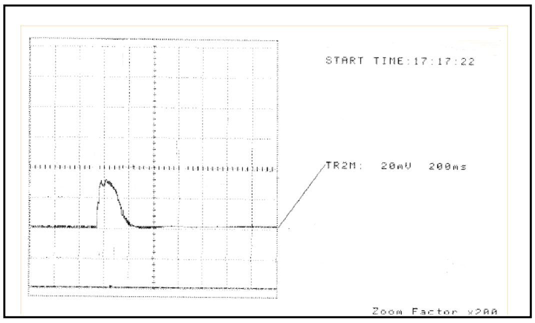

Fig. 3. Figure 2 Hump Waveform

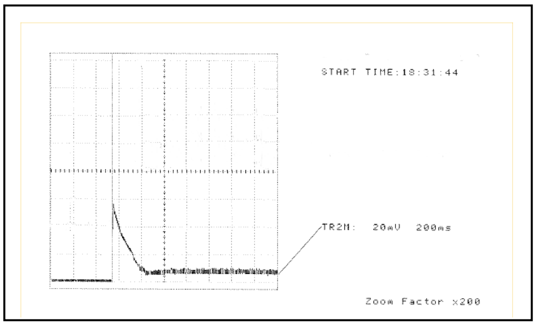

Fig. 4. Figure 3 Sail Waveform

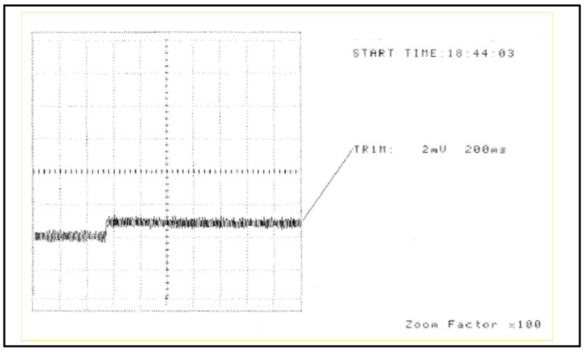

Fig. 5. Figure 4 Step waveform

As shown in Table 1 there is a definite trend from the normal Asymptotic waveform to the Step waveform with decreasing magnetic field.

Looking at these results, we believe that there is a fundamental change in the discharge once the magnetic field is reduced below a certain value. We believe that in this experiment we are in fact seeing two discharges. Above a certain field the discharge is stable and of the Asymptotic form. However as we reduce the field the discharge becomes less stable, and the discharge loses its sharp peak and the long tail, giving the characteristic “hump” shape. As we reduce the field further, this changes again to the triangular “Sail” shape with no tail but again a sharp peak. Finally as we reduce the field even further, the discharge changes once again to a simple step discharge, where the discharge is flat and slowly diminishing.

TABLE 1. Waveform type v Applied Field (5kV). The numbers show the number of times a pulse had the stated waveform.

Gauss	Asymp.	Hump	Sail	Step
650	6			
600	2		4	
550		3	2	1
500	1	1	3	1
475		1	5	
450		1	1	4
440				6

Looking at the physics of the SIM, 350 Gauss should be more than enough to give a stable discharge, and there seems no reason for a second noisy discharge to occur. We speculate that it may be that the energy in the discharge rises to a sufficient level that it causes secondary outgassing of the electrode surfaces, which then produces the noisy asymptotic waveform. If true it could be argued that this should show a discontinuity in the calibration trend of the device as the extra gases produced should increase the apparent local pressure and in turn affect the peak value of the discharge. This effect however was not seen. However we believe that this may be due to the necessary short time delay for gases to be released from the surfaces, resulting in the peak value of the discharge being unaffected, but the "tail" of the discharge being affected, giving a long period of decaying pressure as the arc outgases and then pumps the device. We believe that this gives a credible explanation of what is, in fact, seen in the results.

B. Peak Current v Voltage Relationship SIM Discharge

We then studied the Peak Current v Voltage relationship which shows an inversion of the relationship between 3kV and 5kV for a magnetic field of 700 Gauss. Varying the magnetic field between 650 Gauss and 750 Gauss did not significantly affect this point.

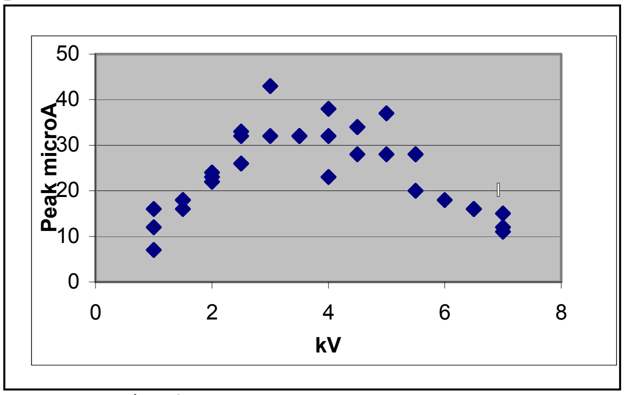

Fig. 6. Peak Current v Voltage results

As can be seen in Figure 6, below 2.5kV there is a clear increase of discharge current with increasing voltage, and above 5kV there is a clear decrease in discharge current with increasing voltage. Between 2.5kV and 5kV there is a scattering of results with no discernable trend. At present we cannot explain this reversal of trend for SIM discharges, and note that it does not occur on DIM discharges, but it is a repeatable effect and very precise.

TABLE 2. Waveform v Applied Voltage (700 Gauss). The numbers show the number of times a pulse had the stated waveform.

kV	Asymp.	Hump	Sail	Step
1				3
1.5				3
2				3
2.5	3*			
3	3*			
3.5	3*			
4	3			
4.5	3			
5	3			
5.5	3			
6	3			
6.5	1			2
7				3

Table 2 shows the result of varying the applied voltage for a fixed magnetic field. We only saw two types of discharge – the Asymptotic and the Step form. However we noted that the Asymptotic waveform differed in one aspect for the low voltages and the higher voltages. At the higher voltages the wave was exactly as shown in Figure 1, with no noise, however for 2.5kV 3kV and 3.5kV (shown with an asterisk in table 2) we saw a short period of noise in the early part of the wave which then abruptly stopped after a few hundred milliseconds. This effect was repeatable.

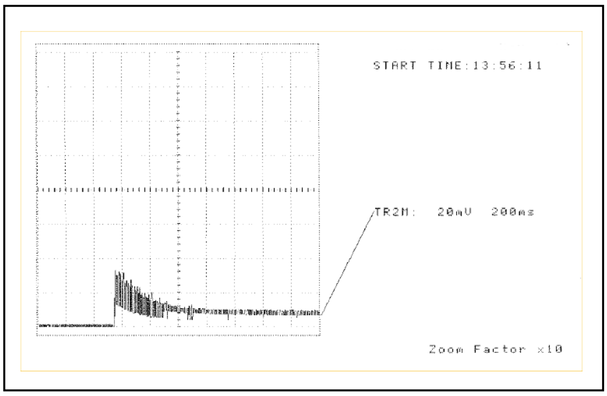

Fig. 7. Noisy asymptotic waveform

The waveform at higher voltages was of the Asymptotic type (Figure 2) and reduced steadily in amplitude until it became the Ramp type (Figure 5). We did not see the other waveforms described in A. It seems that the change from an Asymptotic waveform to a Ramp waveform is a function of the voltage applied. The two intermediate waveforms, Hump and Sail are a product of changing the Magnetic field only. We believe that in this experiment we are in fact seeing one discharge which as we reduce the voltage gives rise to increasing instability first shown by the noisy Asymptotic discharge (Figure 7) and then by the Step waveform,

V. FURTHER WORK

We will next investigate the number of anomalies identified for Double Inverse Magnetron discharges and attempt to understand them more clearly in order to provide a theoretical explanation.

ACKNOWLEDGEMENT

We would like to give our thanks to the other members of VIL who assisted with this work.

REFERENCES

[1] Falkingham L. T. et al "Studies in Inverse Magnetron Discharges of Vacuum Interrupters: Part 1 – Variations in Electric Field" ISDEIV XXIII Conference Bucharest, 2008

[2] Falkingham L. T. et al "Studies in Inverse Magnetron Discharges of Vacuum Interrupters: Part 2 – Variations in Magnetic Field" ISDEIV XXIV Conference Braunschweig, 2010

[3] 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

[4] Weston G. F. Ultrahigh Vacuum Practice, Butterworths, 1985.

[5] Penning F. M. & Nienhuis K. Philips Technical Review No. 11, p116, 1949

[6] Slade P. G. The Vacuum Interrupter Theory, Design, Application, CRC Press, p 243, 2008

E-MAIL OF THE AUTHOR(S): REEVES@VIL.ORG.UK