The effect of magnetron discharge pressure measurement on the actual pressure in vacuum interrupters

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***Abstract*—Vacuum interrupters (VI) have proved extremely reliable over the past 60 years, but failure can occur, and is most often a consequence of loss of vacuum. If the vacuum pressure rises above a critical level, the dielectric strength of the vacuum collapses, resulting in functional failure of the vacuum interrupter.**

During manufacture the vacuum pressure of a VI is measured by stimulating an inverse magnetron discharge inside it. This has long been known to have the effect of pumping some or all of the gas away, but this effect has been believed to be temporary with the original pressure recovering within hours. We have found that with the majority of a sample of old VI, magnetron pumping can be very significant if the discharge is kept going for long enough, and the pressure can be reduced to a very low level. We also found when we tested the VI again two years later, that in the majority of cases the pumping appeared to have been permanent. There was only a slight pressure rise, which was assumed to be due to new gas slowly being desorbed from the solid materials of the VI.

Keywords—vacuum interrupter; magnetron discharge; vacuum measurement; service life, VCB

I. Introduction

A. Pressure rise in interrupters

Vacuum interrupters (VI) are generally assembled by brazing in a vacuum furnace. This permanently seals them with a vacuum pressure in the region of $1x10^{-6}$ mbar. Over the service life of the VI the pressure normally slowly rises, which has been stated by Gentsch and Fugel to be due to the slow desorption at a steady rate of gases absorbed within the solid metals and glass/ceramics from which the interrupter is made [1]. A small part of the pressure rise is also stated to be due to diffusion of helium through the thin metal walls of the VI's stainless steel bellows.

The vacuum provides high voltage insulation between the contacts when they are open. If the pressure should rise to a level much in excess $5x10^{-3}$ mbar the service voltage will not be withstood when contacts are open, and current will flash over, leading to failure to interrupt and potentially to the destruction of the device.

VI have proved extremely reliable in service, but when they do fail the most common cause is degradation of vacuum. A service vacuum life of 20 years is normally stated, but this is a conservative estimate and in most of the old interrupters that we have examined, which are at least 30 years old, the vacuum level has risen significantly from the assumed initial level, but is still well below the critical level, and the VI is still fully functional.

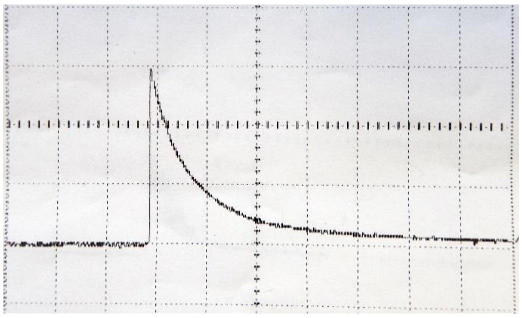

Fig. 1. A typical magnetron pulse. The timebase is 200 ms per division. The vertical scale is $2x10^{-5}$ mbar per division. The peak value measures the vacuum pressure in the interrupter. At the end of the trace there is a small remanent pressure above the baseline.

B. Virtual leaks and real leaks

Loss of vacuum can be due to a Real Leak which consists of gas entering from outside of the VI, but this is extremely rare. Small rises in pressure due to apparent leaks are more normal, and are due to outgassing of components, or trapped contaminants within the sealed device. These are commonly referred to as Virtual Leaks.

C. The magnetron discharge

Manufacturers check the vacuum level of newly made VI using an inverse magnetron apparatus. The VI is placed in a magnetic field coil and a voltage of a few kV is applied across the specimen. The field causes electrons resulting from a first chance ionization event to travel in circles within the vacuum, effectively extending the mean free path a thousand fold or more and enabling a cascade of ionizations to occur. A pulse of current then passes which is proportional to the vacuum pressure. Fig. 1 shows a typical pulse form. The peak of the pulse is used as a measure of the vacuum level. The magnetron technique is described in more detail in [1].

A well-known feature of the pulse is that after the initial rapid rise the current decays over a second or two, indicating that the pressure of gas falls as the discharge continues. It seems likely that the discharge is localized to a small volume within the interrupter where the electric field is concentrated, and over a second or so a large proportion of the gas particles within the VI find their way by thermal motion into this volume and stand a good chance of being ionized and forming part of the pulse.

D. Magnetron pumping

If a second measurement is made after a delay of a minute or so, the new pulse will be found to be much smaller than the first one, indicating an improved vacuum. This effect is well known and is called magnetron pumping. The mechanism of this is discussed later in the paper.

E. Vacuum measurement in production

Production practice varies from company to company. Typically a first single magnetron measurement is made, and if the vacuum level is good enough to pass, the interrupter is stored in air or pressurized gas for a period and retested. The change in pressure is extrapolated for a period, normally 20 years, and the interrupter is passed for sale if the calculated result is safely below the critical pressure.

F. Temporary and permanent gases

It is widely assumed in production testing that the pressure drop seen in the magnetron discharge curve is temporary and that the pressure returns to its original level within a few hours or days. It is also widely believed that VI contain both permanent and temporary gases. The temporary gases can be destroyed by magnetron pumping as described above, but the permanent gases, which might be argon or helium, cannot. The results reported here indicate that in many interrupters these assumptions need clarifying.

II. PRESSURE MEASUREMENTS ON OLD INTERRUPTERS

Data was accumulated on a batch of old interrupters (sealed off over 30 years ago) which indicated that it is possible to use magnetron pumping to reduce their pressures to levels typical of newly made interrupters. By measuring the vacuum levels on a first occasion and two years later we found that the vacuum improvement was maintained and that pressure rise during the two years was at a similar rate to that seen in new interrupters as they age.

A. The sample

In 2013 a number of interrupters were obtained that had been in service for between 30 and 40 years, but were no longer required by their users, for example because a substation was no longer in use. They were V8 types manufactured by Vacuum Interrupters Limited between 1975 and 1985.

The vacuum levels of these VI were measured on receipt in 2013, using this company's standard methodology. The VI were all of the same type, and were manufactured under the same conditions. Three of the VI showed relatively high pressures and behaved quite differently from the others, with indications of the presence of permanent gases. These three were set aside for a programme of experiments concerning permanent gases, which will be reported on when complete. This left a batch of 16 VI which form the subject of this paper. Two years after the reception tests the 16 VI were tested again to see what had happened to their pressures.

B. The measurement procedure used for the 2013 tests

For each VI three magnetron measurements were made on one occasion and a second three measurements were made one week later. There was a one minute pause between each measurement in a set of three. It often happened that no second or third pulse was obtained. This is because when the vacuum is very good the pulse level can be so low that it is comparable with the instrumental noise and cannot be detected, or it can take too long a time for a pulse to arrive. Absence of a pulse within one minute is taken as an indication that the pressure is very low, somewhat below $1x10^{-6}$ mbar.

C. The measurements made

Table 1 shows the measurements made on the 16 VI plus the 3 which were set aside. The six columns under the heading Reception Pressure Measurements record the pressures measured, in mbar, in 2013. Blank cells indicate that no pulse was obtained and the vacuum was assumed to be very good.

It can be seen that all of the VI had a relatively good vacuum. The highest pressure found (specimen T202) was $1.6x10^{-4}$ mbar, which is well below the critical limit for use. It can also be seen that the magnetron discharge pumped all of them down to a low pressure, mostly in the 10^{-7} mbar range. We refer to the last pressure reading (i.e. the peak of the last pulse obtained) as the VI's pumped pressure.

Approximately two years later the pressures were measured again. This time only one reading was taken, for reasons which are explained later. The results are shown in the column headed Pressures Two Years Later (2015) in the table. In these measurements a pulse was obtained every time even though the pressures were very low, which was believed to be due to improvements made to the magnetron measuring equipment during the intervening two years.

All the 2015 pressures were a little higher than the corresponding pumped pressure from two years before, indicating some pressure return, but the pressures were still very low, in the 10^{-7} mbar range or in the low 10^{-6} range. In all cases there was no substantial return of pressure to the levels first measured, indicating that these interrupters were effectively permanently pumped by the first set of measurements.

D. The annual rate of pressure rise for each VI.

The annual rate of pressure rise of each VI was calculated in mbar per year by assuming that the 2013 measurements reduced the pressures to very low values and dividing the 2015 pressures by 2. The results are shown in the ninth column of the table.

E. Calculation of the ages of the VI

If the same rate of pressure rise occurred throughout the life of each VI then its first pressure measured (column 2) would equal its age in years in 2013 times its rate of pressure rise. In other words, its age can be calculated by dividing its first pressure reading by its rate of pressure rise. The calculated ages are shown in the last column of the table.

If these ages are consistent with the actual ages of the VI, then this is evidence that the pressure rise did in fact continue steadily through the lives of the VI except when the pressure was reset by the magnetron pumping in 2013.

TABLE 1 PRESSURE MEASUREMENT READINGS ON OLD VACUUM INTERRUPTERS

Specimen	**Reception Pressure Measurements (2013) mbar**						**Pressure Two Years Later (2015) mbar**	**Rate of pressure rise Mbar/year**	**Calculated ages of the VI in 2013 years**
	First day			***7 days later***					
T194	1.9E-05	2.0E-07		2.5E-07			7.0E-07	3.5E-07	54
T196	2.4E-05			3.0E-07			6.0E-07	3.0E-07	80
T197	2.0E-05			5.0E-07			6.0E-07	3.0E-07	66
T198	4.6E-05	4.0E-07		6.0E-07			7.0E-07	3.5E-07	131
T199	9.4E-05	6.0E-07		1.4E-06			3.4E-06	1.7E-06	55
T200	4.6E-05	4.0E-07		6.0E-07			9.0E-07	4.5E-07	102
T202	1.6E-04	1.6E-06	2.00E-07	5.0E-06			9.8E-06	4.9E-06	33
T203	2.3E-05	1.0E-07		5.0E-07			1.7E-06	8.5E-07	27
T204	4.0E-05	4.0E-07		4.0E-07			1.6E-06	8.0E-07	50
T205	2.2E-05			4.0E-07			4.0E-07	2.0E-07	110
T206	1.8E-05	1.0E-07		4.0E-07			8.0E-07	4.0E-07	45
T207	2.4E-05			8.0E-07			9.0E-07	4.5E-07	53
T208	4.4E-05	4.0E-07					2.4E-06	1.2E-07	36
T210	6.0E-05	2.0E-07		3.0E-06			3.4E-06	1.7E-06	35
T211	2.0E-05	2.0E-07					1.8E-06	9.0E-07	22
T213	4.0E-05			1.0E-06			1.0E-05	5.0E-06	8
VI showing evidence of permanent gas and not included in the experiments									
T162	1.4E-03	1.3E-04	1.2E-04	2.0E-04	1.2E-04	1.0E-04			
T192	2.0E-03	2E-05	5E-06	1.6E-04	1E-06				
T209	3.0E-04	3.0E-06		1.9E-05					

The actual ages of the individual VI are unknown, but as the substations were commissioned between 1975 and 1985, the VI must have been between 28 and 38 years old in 2012, the average being 33 years. The average calculated age in the table is 57 years.

The calculated and expected ages are certainly of the same order of magnitude, but there is close to a factor of two difference. A possibility is that absorbed gas in the solid parts of a VI is depleted near the surfaces by the pumping during manufacture, and it takes a few years for gas to work its way from the bulk to the surface of the solids, before steady desorption sets in. Another possibility is that finite sources of gas due to internal contamination were depleted in the early years.

F. Experimental errors

There is considerable variation in the ages calculated from the experimental data, but there is some tolerance on these measurements. Pulses are not always as clean and well defined as illustrated in fig. 1, so there is sometimes ambiguity as to what the pulse height is,. Often there are rapid spikes on the pulse which may or may not be genuine parts of the discharge, and the pulse can be misshapen due to the discharge jumping about, as discharges often do (fig. 2). The small pulses at the lowest pressures are comparable in amplitude to the instrumental noise so their peak heights cannot be estimated accurately (fig. 3).

The standard deviation of the mean of the calculated ages is 8 years, so with this small sample there is about a 5% chance that the difference between the calculated and expected mean ages is due to chance.

Within these uncertainties, and the uncertain manufacturing dates of the specimens, we believe that the data supports the idea that the measurement process resets the pressures to their as-new levels, and then pressure return proceeds as from new, i.e. the interrupters are suffering from a very small but constant virtual leak rate.

For 15 of the 16 VI there is no evidence of measurable amounts of permanent gas, and it looks as if the gas seen is all temporary and is pumped away by the testing. It only returns at a very slow rate measured in tens of years. Specimen T213 however shows a rate of pressure return which is 7 times faster than the average of the others. This might be a statistical outlier with a larger virtual leak rate than the others, or possibly it might be that this one does have a small amount of permanent gas which has returned after magnetron pumping.

III. MORE OBSERVATIONS ON MAGNETRON PUMPING

In the pulse shown in Fig. 1 it can be seen that the pressure falls asymptotically from a peak height down to a level which approaches the base line but does not quite reach it. This indicates a remanent pressure level which might be taken to indicate permanent gas which is not pumped by the discharge.

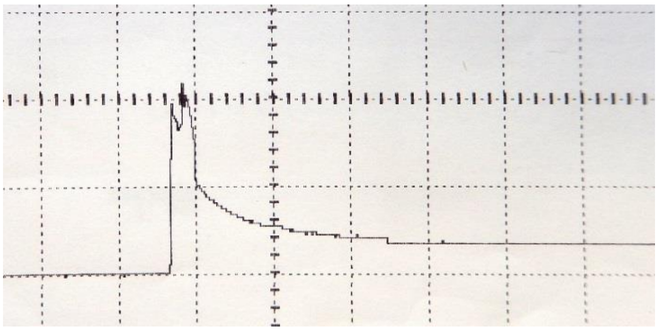

Fig. 2. A badly shaped magnetron pulse. The pulse appears to have jumped from one place to another. The pulse height is difficult to determine.

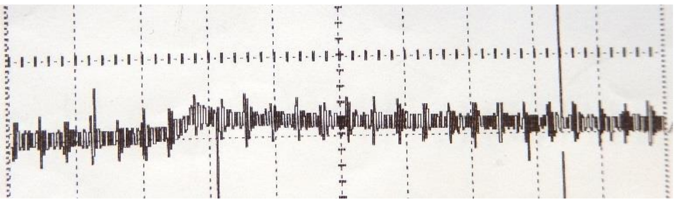

Fig. 3. A small pulse whose peak height is difficult to estimate because it is comparable with the instrumental noise. This pulse represents a pressure of roughly 6x10-7 mbar. From the triggering of the pulse to the right hand edge of the screen is a duration of 1.4s.

It might also be taken to indicate that pumping of temporary gas is not yet complete within the displayed duration of the discharge, and that if the discharge were to be continued longer then the pressure would drop to the limit of detection.

From the triggering of the oscilloscope to the end of recording takes 1.4 seconds in the time base setting used for this work. However this was not the total pumping time a VI received in each test. Once a pulse was complete on the screen the discharge continued for a second or so before the operator switched the field off. This has not been considered important in the past and the time before switching the field off has not been recorded historically.

To investigate this concept a large number of tests were done using different VI in which the discharge was continued for one minute after the trigger pulse and it was found that this nearly always had the effect of pumping the VI down to a very low pressure. If another test was then made within a minute or so this gave a very small or non-existent pulse. We believe that this indicates that second and third tests in the First Day measurements of table 1 do not indicate pressure return, they indicate insufficient pumping in the first test.

A. Pumping of the temporary gas in the experimental batch

The total magnetron pumping time each VI received in the reception tests in 2013 would be 1.4 seconds for each pulse that occurred plus an unknown few seconds of switch-off time. This total of a few seconds pumping seems to have been sufficient to give the very low pressures seen two years later in 2015.

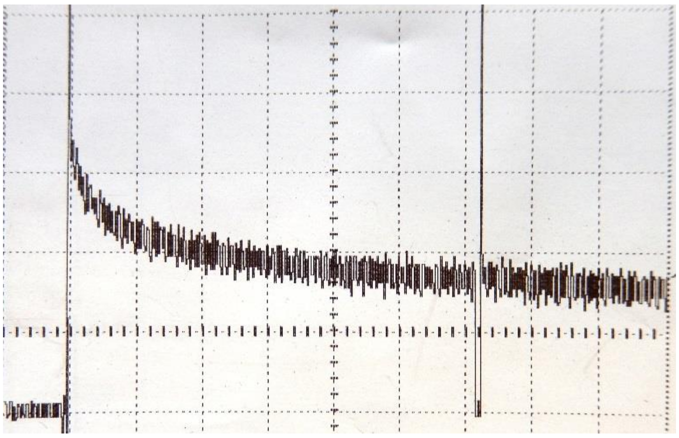

Fig. 4. Pumping for 300s of a VI which has a high level of permanent gas. The initial pulse (off scale) represents a pressure of 4x10-5 mbar. The remanent pressure at the end of the trace shows a pressure of roughly 3.4x10-6 mbar. The event part way along the trace is where magnetic field was switched off monentarily to show that discharge continues from where it left off when the field comes back on. With this particular VI the pressure returns within only a few seconds after magnetron pumping.

In the measurements made after two years the procedure was adapted to making only one measurement for each VI but continuing the discharge for the longer and definite time of one minute. The intention is that these should be very well pumped, and we hope to examine them again in a few years to see if the same rate of pressure return is observed.

B. VI with permanent gas

As mentioned before, with a small number of VI there is a genuine remanent pressure level and the pressure returns substantially to the original reading within a time period measured in hours. This indicates indestructible permanent gas. Using a VI that has a large amount of permanent gas, a trace was made with its time base 100 times slower than normally used, so the pulse was continued for 3 minutes (fig 4). It can be seen that the pressure continues to fall during all this time, but that there was still a clear remanent level at the end of all this pumping. This is quite different to the pulse seen in Fig. 1 where the pulse drops nearly to the pre-discharge level i.e. zero. It should be possible with a suitable magnetron procedure to obtain separate measures of temporary and permanent gas in a VI.

IV. DISCUSSION

In the past it has generally been thought that magnetron pumping is temporary, and that the effect is lost and the pressure returns within a few hours or days. The pressure drop was assumed to be due to ionized gas molecules being adhered electrostatically to solid surfaces and then being released over time as the charges became neutralized and the molecules re-entered the vacuum by way of thermal agitation.

The findings presented here from a relatively small sample of VI indicate that most of these VI contain only destructible temporary gases in significant amounts, which can be effectively removed by extending the duration of a magnetron discharge used to measure the vacuum pressure.

It seems that for most VI these temporary gases are evolved internally at a fairly constant rate, in accordance with Gentsch and Fugel's statement, and that after magnetron pumping the pressure continues to rise at this rate.

In view of this effectively permanent pumping, we believe that a different pumping mechanism seems more likely, in which the discharge breaks up molecules such as O_2, N_2, H_2O, CO_2 and organic residues into ionized monatomic fragments, which are highly reactive chemically. These combine permanently with the very clean copper, chromium and stainless steel parts within the VI to form solid chemical compounds. In addition, during electrical processing in manufacture metallic chromium and copper may be evaporated from the contacts and condense on surfaces inside the VI to form very clean reactive deposits, which can trap or bury gas molecules. This may also happen during switching operations in service.

A small minority of the VI examined did however contain significant amounts of permanent gas. We expect an extended magnetron discharge to remove effectively all the temporary gases from such VI, after which any remanent level will reveal the presence of the permanent gas. VI with permanent gas may be a result of inadvertent contamination during manufacture, and will be subjected to further investigation, to be described in a later paper.

Continued study along these lines leading to a full understanding of magnetron pumping and pressure return might enable manufacturers to create a more controlled vacuum regime within the VI and lead to longer stated service lives than the 20 years which has been customary since the 1960s.

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