An appraisal of the insulation capability of vacuum interrupters after long periods of service

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Abstract- **Vacuum Interrupters (VI) have been the dominant switching device in medium voltage switchgear for the past 30 years. They have proved very reliable and many have been in service well beyond the 20 year service lives that manufacturers assigned to them. We have examined over 200 life-expired VI withdrawn from service for checking. The only end-of-life failure mechanism found was degradation of vacuum. About seven percent had such poor vacuum that they either did not withstand test voltage or they would be expected to fail quite soon. This is a very high rate of failure compared to that reported for VI within their design life of 20 years, and implies that the sample may be showing signs of end of life faults.**

I. Introduction

A. *Vacuum interrupters in switchgear*

Vacuum Interrupters (VI) were introduced into medium voltage switchgear about fifty years ago and came to dominate the market, having displaced interrupters using air or oil as the switching medium.

VI have normally been assigned a service life of twenty years by their manufacturers. All vacuum devices suffer degradation of vacuum over time and twenty years was a conservative estimate of the period for which the vacuum should remain good enough for service. Hundreds of thousands of VI have now been in service for twenty years and many have considerably exceeded this period. The question we should now ask is “How long can VI reasonably be kept in service?”

B. *The problem of ageing interrupters*

Failure rates of manufactured devices generally follow the so-called bathtub curve (Fig. 1), which splits the life of a device into three phases. The first phase is immediately after manufacture where a product has an initial high rate of failure, principally caused by manufacturing faults revealing themselves. These *initial faults* are often not too troublesome for the purchaser because they are generally captured by the manufacturer’s quality system and switchgear commissioning on site.

After this, during the second phase the rate of failure falls to a low steady level considered *Normal*, and that continues for some time.

Eventually at the third phase, *end of life faults* begin to appear, and the rate of faults rises until the devices can no longer be considered to be reliable, and need to be repaired or replaced.

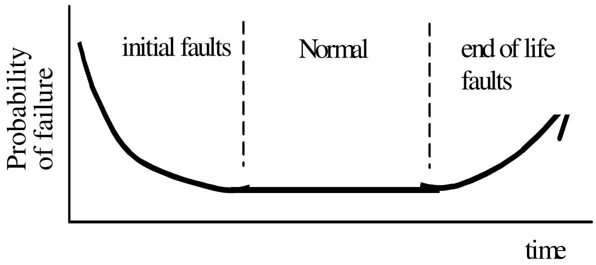

Fig. 1. The bathtub curve for failure rates of an industrial product

In the case of vacuum interrupters in service there is as yet no indication of large numbers of end of life faults arising, though it should be noted that there is no well established system for reporting them. However all vacuum devices, such as cathode ray tubes and electronic valves, are known to fail eventually by loss of vacuum, which may be part of the reason why these products are now obsolete.

The objective of this paper is to investigate the bathtub curve, as far as vacuum level in VI is concerned, and to establish at what point the failure rate starts to rise significantly, indicating that the third phase of life is starting. This is important because as the population of old VI in service increases it is necessary to decide at what point the VI and possibly its vacuum switchgear should be replaced to avoid significant numbers failing in service. Oil and gas insulated circuit breakers have built in means to check on the presence of the insulating medium, but VI do not include any means to monitor their vacuum state. The tests we report here show the degree to which vacuum has deteriorated in a sample of VI and this information makes a step towards being able to make a risk assessment for an installation.

C. *The consequences of failure*

In most service applications VI are normally closed, allowing current to flow. In this state loss of vacuum is not catastrophic, and may not even be noticed until the VI is called upon to interrupt current. However in the case where a full short circuit has occurred, and the VI is required to open in order to protect the circuit, poor vacuum can lead to a failure to interrupt and possible destruction of the switchgear.

D. *Vacuum as an insulator*

When the interrupter contacts have separated for switching, they then need to withstand the service voltage. With vacuum between the contacts the separation required is only a few millimetres

A vacuum provides good electrical insulation because there is in principle nothing present that could conduct electricity, and this gives a very high dielectric strength. The physics of vacuum insulation is described in [1]. In practice an absolute vacuum cannot be achieved; readily available pumping systems can pump down to a pressure around $1x10^{-7}$mbar, and VI are normally sealed off with a pressure of the order of 10^{-6}mbar. The degree of vacuum is critical to the correct operation of the VI, as the dielectric strength of a vacuum gap varies in a very non-linear manner with the pressure.

This is displayed in the Paschen curve, Fig. 2 and [2]. As the pressure is decreased from around $2x10^{-3}$ mbar the breakdown strength remains high and constant. In the case shown this is around 380kV/cm, a level set by electron emission from surfaces, and not dependent on gas molecules. As the pressure rises from $2x10^{-3}$mbar towards 10^{-2}mbar, the breakdown strength falls very rapidly, and at 10^{-1} mbar it is almost zero[1]. Vacuum interrupters are generally considered to have failed if the pressure rises to a level that is outside the flat portion of the Paschen curve i.e. a pressure higher than about $2x10^{-3}$mbar.

E. The implications for VI

Degradation of vacuum can occur by way of a real leak or a virtual leak. Very small real leaks can occur for example when VI are sealed by brazing, due to a small area of porous braze, or by corrosion of the metal sealing components, allowing gas to enter the VI from outside. Virtual leaks can occur for example by diffusion of trapped gases from solid parts, or breakdown of organic contaminants within the VI due to inadequate cleaning; these cause a rise in pressure within the VI although there is no actual leak path from outside of the VI.

It can be seen from Fig. 2 that if a VI is made with an initial pressure of $1x10^{-6}$mbar, the pressure may rise over its service life to $1x10^{-3}$mbar without any effect at all on its electrical performance. After $1x10^{-3}$mbar however, an unsafe condition can be reached very rapidly as pressure increases. This is the so-called “Paschen cliff”. In quality checking new VI manufacturers typically measure the pressure in each VI on two occasions a few days apart. Suppose a pressure of $3x10^{-6}$mbar is measured on the first occasion, and $4x10^{-6}$mbar one week later. The rate of pressure rise is $1x10^{-6}$mbar per week, which would be calculated to lead to a pressure of $1x10^{-3}$mbar in 1000 weeks, or 20 years. This VI would just pass the quality requirement for a minimum 20 year life.

[1] As pressure is increased further above this level the density of molecules impedes the ability of ions to accelerate to high speeds, leading to air being a good insulator at atmospheric pressure

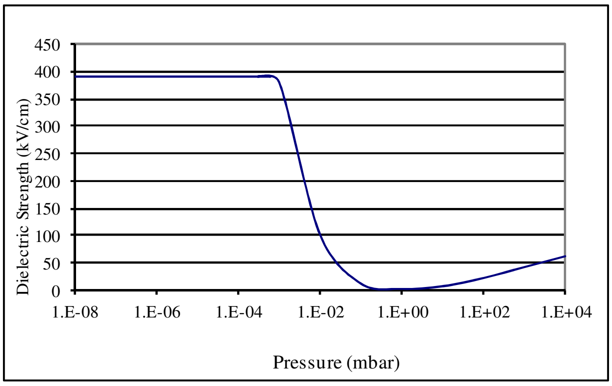

Fig. 2. The Paschen curve, showing how the electrical conductivity of a gas varies with pressure.

F. Assessing the state of installed vacuum interrupters

Quite often periodic maintenance of the switchgear is carried out, which includes an AC or DC high voltage test across each VI in the open position (the HT test). The problem with this is that it only reveals if the vacuum has already risen to an unsafe level, and this could have happened at any time since the last test. If this test is passed, the pressure could still be just under the point of failure.

Today there is a widespread move to condition based maintenance, which means less periodic checking and more reliance on information on the condition of the equipment. At present VI do not have a way of signaling approaching or actual failure. However if data on VI failure rates was available it could be used statistically to assess the status of VI in a risk-based condition-based maintenance scheme.

II. OUR STUDY OF AGEING INTERRUPTERS

We present the results of vacuum level measurements on 207 vacuum interrupters that have been in service for periods ranging from 25 years to 40 years.

A. The sample of tested interrupters

Most of the VI in the sample were sent to us by their owners for inspection and revalidation. The VI had to be removed temporarily from service. We generally know roughly when each type of VI was manufactured, but we usually have no information about the exact date of manufacture or the detailed service history of the individual VI tested.

B. Vacuum measurement for revalidation

In manufacture VI have to be held at a high temperature for some time to drive out adsorbed gases. This is normally done by assembling them in a vacuum brazing furnace, so they are pumped and sealed in one operation. For quality checking the vacuum level in a VI has to be measured non-invasively. This is done using the magnetron effect, whereby a magnetic field is used to greatly increase the conductivity of the residual gas in the VI [3]. Our magnetron test replicates the original test used by most manufacturers.

C. Data presentation

In a previous paper [4] we reported on the vacuum pressures found in a sample of 140 VI. The pressures ranged from less than $1x10^{-6}$mbar to over $1x10^{-3}$mbar. The number in each decade of pressure was reported. The largest group had 57 VI with pressures in the range $1x10^{-4}$mbar to $9x10^{-4}$mbar. Now this group is important because if most were at the upper part of the range, with pressures of $9x10^{-4}$mbar, their pressures could shortly rise to over $1x10^{-3}$mbar, whereas if most were in the lower part of the range at $1x10^{-4}$mbar it would take 10 times as long for this to happen. A finer breakdown of the pressure ranges was needed.

In the present paper we divide each decade of pressure into three parts, equally spaced logarithmically. Table 1 shows the pressure ranges we now use in presenting the data, which is in Fig. 2. Sometimes when the vacuum is very good no magnetron signal is produced within a reasonable period; in these cases the pressure is recorded as being in range A of Table 1: *less than $1x10^{-6}$ mbar*. Also included in range A are those interrupters with a signal indicating a pressure of less than $1x10^{-6}$ mbar. Our equipment can measure pressures down to about $1x10^{-7}$ mbar.

Before measuring vacuum pressure we always apply a voltage test. 10kV dc is applied across the VI. If significant current flows, then the pressure is too high for the VI to be used, and also too high for the magnetron test to be safely carried out. These cases are put in pressure range N: *HT test fail*.

TABLE 1. Pressure ranges in Fig 2

Pressure range	mbar
A	less than 1x10-6
B	1 to 2.14 x10-6
C	2.15 to 4.6 x10-6
D	4.64 to 9.9 x10-6
E	1 to 2.14 x10-5
F	2.15 to 4.6 x10-5
G	4.64 to 9.9 x10-5
H	1 to 2.10 x10-4
I	2.15 to 4.6 x10-4
J	4.64 to 9.9 x10-4
K	1 to 2.14 x10-3
L	2.15 to 4.6 x10-3
M	4.64 to 9.9 x10-3
N	HT test fail

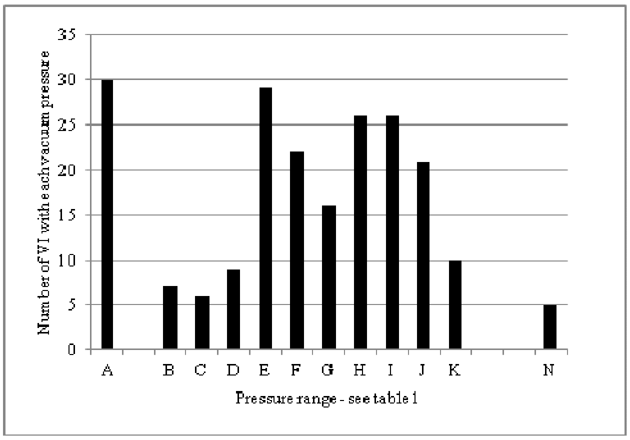

Fig. 2. Vacuum pressures in 207 long service VI

D. The results

In this sample we found no examples of corrosion or of mechanical damage. Degradation of vacuum to some degree was found in most of the sample, as shown in Fig 2. Our sample includes three main types from two manufacturers, plus a miscellaneous group. The four subgroups all showed a similar distribution of readings.

E. Discussion of the results

All the VI sent to us for examination were over 30 years old and were believed to be good for service by their owners, and yet five of them failed the HT test and were therefore definitely not fit for service.

Another ten (range K) were near or possibly just over the Paschen cliff. We define these as *vacuum fails* and they are also no longer fit for service.

Forty-three of the VI (ranges A, B and C) had pressures similar to what we believe they had when new.

One hundred and twenty eight of the VI (ranges D to I) showed significant pressure rise, up to a maximum of $4.63x10\text{-}^{4}$mbar. Suppose a VI with this pressure was 20 years old, and that the same rate of leakage continued. In another 20 years the pressure would rise to $9.2x10^{-4}$mbar, just under the Paschen cliff. We therefore rate all these as fit for another 20 years of service.

The critical range is range J, 4.64 to $9.9x10\text{-}^{4}$mbar, where there are 21 VI. At the lower end of this range the VI can still be seen to be good for another 20 years, but at the upper end of the range we are more cautious and rate them as good for another 10 years only. By examining the individual measurements, 11 of the VI in the sample were rated for 10 years.

III. MEAN TIME TO FAILURE OF THE SAMPLE

It is generally believed that vacuum interrupters are extremely reliable, with mean time to failure (MTTF) of the order of 40,000 interrupter years being quoted [5].

MTTF is defined in various ways. Manufacturers of

VI calculate MTTF by adding up the service years accumulated by all VI sold up to a given date, and dividing by the number of failures over that period that have come to their attention.

Applying this definition to our sample, we assume that the VI have served on average for 30 years, giving total service years of 207x30 = 6210 interrupter-years. The five HT fails would then give an MTTF of 6210/5 = 1242 interrupter years.

However, counting in the ten vacuum fails, the MTTF is 6010/15 = 414 interrupter years.

A. Discussion of our MTTF result

There is clearly a huge difference between the MTTF we have found and that reported by the manufacturers. We believe that this large difference is due to the difference in the service ages of the interrupters. We presume that the manufacturers' data concerns VI within their rated service lives, whereas ours is for VI that are significantly beyond their rated service lives.

IV. CONCLUSIONS

The majority of the sample had a worsening in vacuum level compared to the seal off pressure. In most cases this was not significant as their pressures were in the flat part of the Paschen curve and did not affect their voltage withstand capability.

However the significant finding was that the level of failure found was much higher than expected from the failure rates reported during the service life of 20 years, which appears to indicate that and end of life failure mechanisms may be occurring.

The large difference in failure rates found between old VI in our sample and "in service life" VI indicates that as VI age beyond their nominal service lives the probability of vacuum failure increases significantly.

We now intend to increase our sample size and also to review the data with a view to confirming or not the hypothesis that end of life mechanisms are occurring and what they may be.

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