VACUUM LIFE ASSESSMENT OF A SAMPLE OF LONG SERVICE VACUUM INTERRUPTERS

Leslie FALKINGHAM
Vacuum Interrupters Ltd – UK
falkingham@vil.org.uk

Richard REEVES
Vacuum Interrupters Ltd – UK
reeves@vil.org.uk

ABSTRACT

The electricity distribution industry relies on an ageing population of vacuum interrupters. It is reasonable to ask the question "how long can vacuum interrupters continue to be used?" In order to answer this, the basic principles of a vacuum interrupter and vacuum insulation are outlined, and the difficulty of establishing whether the vacuum will still be good for a further period of use is explained. The shortcomings of the high voltage withstand test which is currently relied on as an indicator of vacuum condition are pointed out. A technique to assess the remaining life of old vacuum interrupters using a vacuum measurement apparatus is briefly described, and results are presented for a typical sample of nine long service interrupters of three types that have been in service for between twenty-five and almost forty years. It was found that some could be certified for another 20 years of use, some for a lesser period, and one should be immediately replaced. It is concluded that revalidation of interrupters in this way is a viable technique and allows their continued use for an extended period.

INTRODUCTION

Vacuum Interrupters (VI) were first used as the key current switching element in medium voltage switchgear over 40 years ago and over time this has become the dominant technology in medium voltage switchgear. Originally the VI manufacturers generally gave the VI a 20-year "vacuum life" [1]. This was based on a sophisticated vacuum measuring system and leak rate assessment made during the manufacturing process. Now that increasing numbers of interrupters have been in service for much longer than this, it is time to consider how their present vacuum condition could be tested in order to predict how much longer operators can prudently leave them in service. This question was first raised over 10 years ago by Belnaves [2], but until now it has remained generally unanswered.

Vacuum interrupter basics

VI are sealed-for-life vacuum devices. This means that they are pumped down to an appropriate level of vacuum and then sealed off. After sealing there is no further significant active pumping; they rely on their hermetic sealing to maintain a good enough vacuum level for operation.
The vacuum insulation is fundamental to the operation of vacuum interrupters, and it is necessary to explain both what we mean by vacuum, and also the effect of loss of vacuum on performance. The design of vacuum interrupters has been described in detail elsewhere [3], but a brief description here is necessary for understanding.

Vacuum Interrupter Design and operation
A typical VI is shown in Figure 1. It consists of two electrical contacts at the ends of thick copper conductors, which can be moved apart by the switchgear mechanism. The contacts are sealed into a vacuum container. One of the conductors has a metal bellows attached that allows the necessary movement of the contact.
VI are nowadays made by a very thorough process in which the component parts are assembled in a vacuum furnace, which is pumped to a very high vacuum. The heat "outgases" the components, driving any dissolved gases or moisture into the pumps, and then as the heat is increased, it brazes the components together. However in the past a number of other techniques were used by various manufacturers, which must be taken into account.

Due to the extremely high dielectric strength of a vacuum, it is normally necessary to open the contacts only 6-8mm for 12 kV systems and 12mm for 36kV systems.

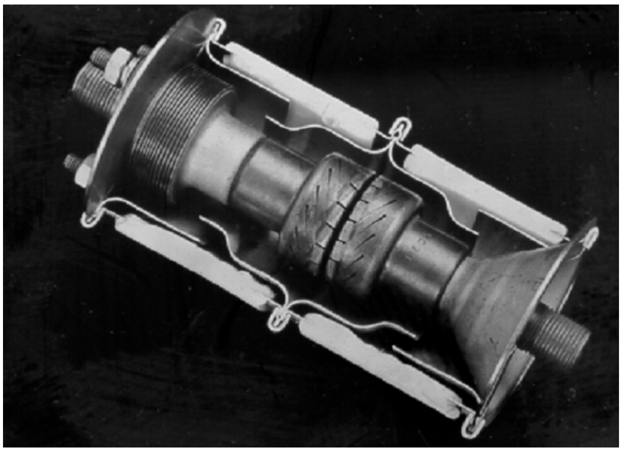

Figure 1: A Sectioned Vacuum Interrupter

The Effect of Vacuum Level on Performance
We need to consider how good a vacuum is required for operation of the VI in service. Fig. 2 shows the "Paschen curve" for dry air. We are interested in the left hand side of the curve, which shows a sudden increase in dielectric strength around 10^{-2}mbar and then a constant dielectric strength for pressures below 10^{-3}mbar. Any pressure lower than about 10^{-3} mbar makes no difference to interrupter performance.
If the pressure within the VI rises over time from the normal manufactured value (usually 10^{-6} mbar) there is no effect until the "limiting value" of 10^{-3}mbar is reached, after

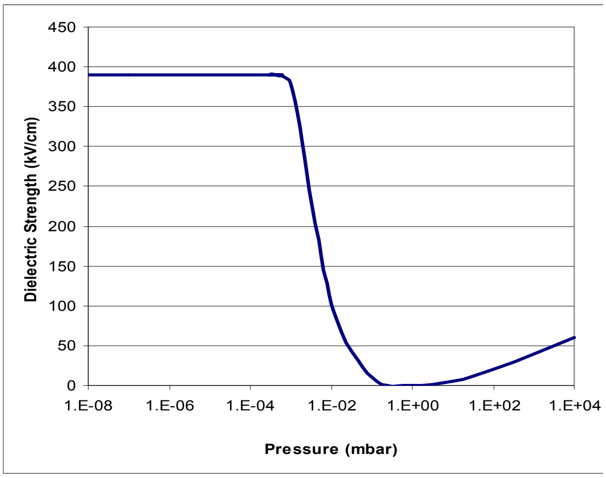

Figure 2: The Paschen Curve, Showing How Breakdown Voltage Varies With Vacuum Pressure. Note that pressure increases to the right, but degree of vacuum increases to the left.

which the insulation effect declines very rapidly with rising pressure. In vacuum interrupter design it is assumed that once an interrupter enters this declining zone it has failed, as it will quickly reach a point where the Transient Recovery Voltage cannot be withstood and the interrupter would then be incapable of interrupting even small currents.

Vacuum Life

During manufacture, following seal-off interrupters are pressure tested using a magnetron pressure tester, Figure 3. An interrupter is placed inside a magnetic field coil, and voltage applied across it. A single small pulse of current passes, whose size is a measure of how much gas is inside the interrupter. Usually a second test is carried out a few days later, and any increase in the pulse size is an indication of leakage. Some leakage can be tolerated if it can be calculated that the pressure will still be within the safe limit in say 20 years time. Such testing equipment is believed to be used now by all manufacturers, but it is factory equipment and not available to users, or for use in the field.
During the calculated vacuum life of the devices (in the industry this is termed the "Storage Life") the manufacturers claim, correctly, that the rigorous manufacturing quality control employed together with careful design mean that loss of vacuum is extremely unlikely and that a simple voltage test is sufficient to prove that the vacuum is intact. However although true for the 20 year Storage Life, this cannot hold true indefinitely. Put simply, if you keep any piece of equipment in service indefinitely it will eventually fail. What is critically needed now is some idea of when we can expect old VI beyond the design life to start failing. After reaching the critical value it is likely that a closed vacuum interrupter would continue to appear good for some time without any apparent problem, because its normal condition is contacts-closed. However if the switchgear then had to operate, and tried to commutate a short circuit current the failure could be catastrophic. To minimize this possibility the key question is "how can the condition of the vacuum insulation be verified?" Another key question is "can we give a prediction of further service life?"

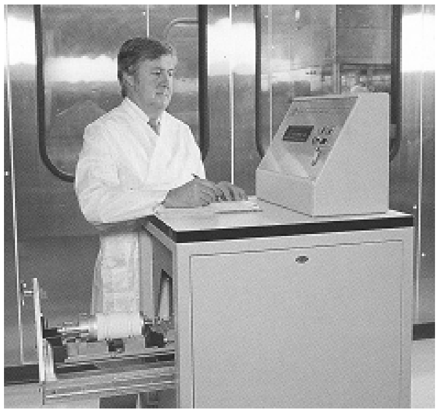

Figure 3: A Magnetron Pressure Measuring Machine in a Factory

The Sealed for Life Concept

In the 1960s high voltage switchgear was designed assuming that maintenance would be carried out on a periodic basis, with extra maintenance for heavy use, much as is still the case for motor cars. The earlier oil based equipment fitted this philosophy very well, requiring regular checking of the oil, and also replacement of the oil and contacts after a small number of short circuit operations. The introduction of vacuum, with its extremely long switching life (>50 operations at 100% short circuit level, and more than 10,000 switching operations) completely removed the need for contact replacement, and led to VI being described by the suppliers as "sealed for life". However for this description to be meaningful the period of life must be defined. This was originally set at 20 years, based on experience with electronic vacuum tubes. This is now the industry standard. As the overall switchgear has a nominal life of 40 years, it was assumed that the VI would be replaced after 20 years in a mid-life service for the switchgear.
Since the 1960s the world of switchgear has changed beyond recognition, with privatisation of the utilities and rationalisation of the switchgear manufacturers. Also users of switchgear are moving from fixed periodic maintenance to condition based maintenance. This works well for other parts of the switchgear, but the sealed-for-life concept of the vacuum insulation just does not fit this philosophy.

The Bathtub Curve

Historically VI have proven to be extremely reliable, but it would be unwise to extrapolate this experience to give an indefinite life. Most devices follow the Bathtub Curve of failure shown in Figure 4. There is a high failure rate for the early part of a product's lifetime, as manufacturing faults shake out, followed by a long period of stable low failure rates, which eventually is followed by a third stage of rising failure rates as age-related effects come into play. This is very familiar to the owners of motor cars. The excellent service experience of VI to date has been mainly within the

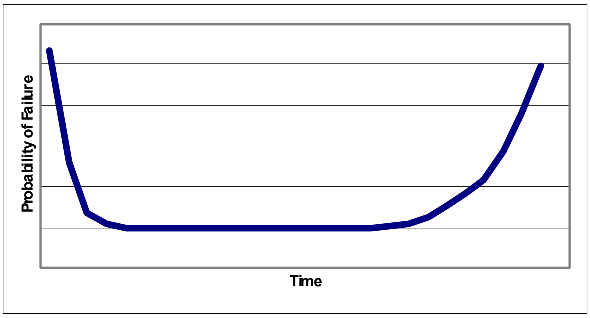

Figure 4: The Bathtub Curve

design life of the VI where the failure rates are expected to be very low. As the devices age they must eventually reach the third part of the bathtub curve and start to fail with increasing probability. Given long enough this will actually reach 100% failure probability. All machines die. The important question is, "how close are we to this third stage of failure?" If we knew this we could continue to use old VI for a period beyond their design life with very low risk.

Leakage mechanisms

Vacuum science is well established and we know that air, gases and vapours can enter a vacuum by a number of mechanisms. Real leaks can arise through porous brazes, through leak paths caused by corrosion or by diffusion of gases through any parts where the metal is too thin. Corrosion leaks can be extremely slow if caused by chemical action along grain boundaries in the metal. Stainless steel is used a lot in making interrupters, but it can be far more susceptible to corrosion than most people think. Virtual leaks occur when gases dissolved in the bulk of metal or ceramic parts, or adsorbed in voids or cracks in them, diffuse out over time. Susceptibility to virtual leaks is influenced by the design of the VI and by the quality of manufacture. We simply do not at the moment have sufficient experimental evidence of what is actually happing inside specific interrupters.

The High Voltage Withstand Test

So far users have had no means of checking the vacuum inside their interrupters. Instead they have applied the High Voltage Withstand Test during periodic maintenance. The contacts are opened and a voltage several times the service voltage is applied. If any current flows, the interrupter is declared unfit for service and is replaced with a new one. The voltage withstand test has two weaknesses:

a) It is a simple pass/fail test, which only tells you if the pressure is now too high. It does not give any indication of how good the pressure is in the pass case, i.e. how much longer the interrupter will be good for;
b) If the test result is a fail, this tells you that the interrupter is already unsafe, and if it had been called upon to interrupt in the period before the test, there could have been a catastrophic failure.

MEASUREMENTS ON A SAMPLE OF INTERRUPTERS DRAWN FROM SERVICE

Equipment

We built a laboratory magnetron vacuum pressure measuring apparatus for testing interrupters, similar to the ones used during manufacture [5]. Magnetic field is supplied by a solenoid using 40 kg of copper wire on a former 180mm long and with a central hole of diameter 250mm. Fig. 5. The coil is of optimised geometry and is powered by a 2kW dc current supply, giving a field of 700 Gauss.

Fig. 5. A vacuum interrupter in the solenoid coil.

The high voltage supply provides up to 10kV, and has a current capacity of 10mA. Normally we test at 5kV. Figure 6 shows the circuit.
The pressure measured is proportional to the height of the current pulse, which may vary from about 2mV to 5000 mV. The captured pulse is displayed on a storage oscilloscope, Fig.7. 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.

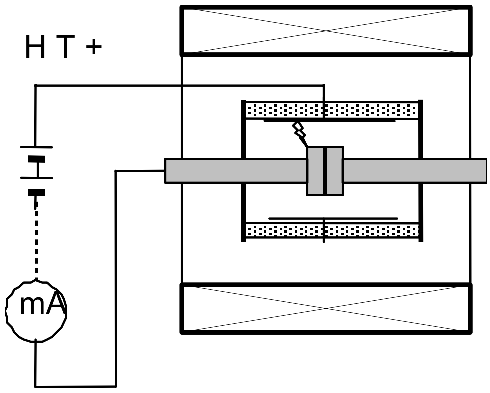

Fig. 6. A schematic Magnetron Circuit.

Procedure

We performed a number of magnetron pressure measurements on each VI to determine the present state of the vacuum and then performed a leak rate calculation of the same kind as used by the manufacturer to verify the original 20 year Shelf Life. In order to validate an extension of the VI life, additional tests on the VI are also necessary but this paper concentrates on the critical vacuum test.

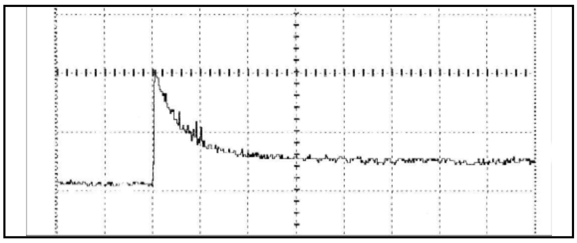

Figure 7. Typical magnetron pulse from an interrupter.

Results from a Sample of Long Service Interrupters

We have tested a large quantity of VI of different types as part of an ongoing project, and here show typical results from a group of 9 interrupters, three each of three different designs. Types A and B had been in service for about 25 years and type C had been in service for over 38 years. The manufacturer's original test results are not available to us, but as pressure is measured on a logarithmic scale we do not actually need to know the original pressure; we can assume that all measured gas in the interrupter is due to leakage. The VI were randomly selected by the users and represent typical in-service interrupters. The pressures measured are shown in table 1.

No.	Type	Pressure in mbar
1	A	$1.8x10^{-5}$
2	A	$1.3x10^{-5}$
3	A	$8.5x10^{-4}$
4	B	$2.4x10^{-4}$
5	B	no pulse
6	B	$2.5x10^{-4}$
7	C	$5.5x10^{-4}$
8	C	$5.6\ x10^{-4}$
9	C	$4.0x10^{-4}$

Table 1. Pressure measurements on a sample of nine long service interrupters of three different types.

Interpretation of the results

We found five classes of interrupter vacuum in our sample;

a) A very good vacuum

Interrupter number 5 in table 1 gave no pulse in the magnetron. At very low pressures a pulse may not strike for a long time, or may be so small as to be hidden within electronic noise. This indicates very good vacuum, better than 10^{-6} mbar. This VI could safely be assigned a further life equal to the manufacturer's original stated life.

b) A small pressure rise

The pressure in interrupter number 1 had risen to $1.8x10^{-5}$ mbar in 25 years. This gives a measure of its leak rate of at worst $1.8x10^{-5}$ in 25 years This means the pressure could rise to $3.6x10^{-5}$ mbar in a further 25 years. This is below the limiting value, and this interrupter too could safely be assigned a further life equal to the manufacturer's original stated value. Interrupter 2 was also in this class.

c) A medium pressure rise

The pressure in interrupter number 4 had risen to $2.4x10^{-4}$ mbar, and could therefore rise to $4.8x10^{-4}$ mbar in another 25 years. Although this appears to be below the limiting value by a factor of 2, we have to take into account that the magnetron is not yet calibrated for this particular model of interrupter, and there are repeatability problems and signal noise. This mean that the measurements are not accurate to better than half a decade. We would therefore assign this interrupter only a limited extra life, such as 10 years, before retesting. Interrupters 6, 7, 8 and 9 also came into this class.

d) A large pressure rise

The pressure in interrupter number 3 was too high for it to be safely used. It should be urgently replaced.

DISCUSSION

There are increasing numbers of interrupters in service today which are considerably older than the original 20 year design life. From our limited results we can conclude that some interrupters are as good as new after long service, some have deteriorating vacuum but can still serve further, and a small proportion are unsafe for further use. The nine VI shown are a representative sample of tests performed on a much larger quantity so far.

VI come in different designs both from different manufacturers and also from design changes over the past 40 years. In order to establish a picture of the state of cohort of VI in service it will be necessary to check a statistically significant number of VI from that cohort. This would provide the vital information necessary to devise a strategy concerning the network. An alternative approach would be to simply test all interrupters which are beyond their original design life, which would remove the uncertainties pertaining to the present maintenance checks for a network operator.

REFERENCES

[1] V.I.L,. 1987 *Data Sheet Type V506 05.0587 Rev. 2,* Vacuum Interrupters Limited, London, UK.

[2] D. Belnaves, "Practicalities of Using SF6 and Vacuum Switchgear" IEE Colloquium on an Update in SF6 and Vacuum Switchgear at Distribution Levels, London, 1996.

[3] P. Slade, 2008, *Vacuum Interrupters: Theory, Design, and Applications*, CRC Press, Boca Raton, USA.

[4] L. T. Falkingham "The Assessment of Vacuum Insulation Condition in Time expired (>20 years old) Vacuum Interrupters and Switches" INSUCON, Birmingham, UK, 2006.