THE ASSESSMENT OF VACUUM INSULATION CONDITION IN TIME EXPIRED (>20 YEARS OLD) VACUUM INTERRUPTERS AND SWITCHES

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Synopsis:

Vacuum switchgear has grown since its first introduction in the late 1960's to become the dominant switching technology for medium voltage switchgear world wide, with hundreds of thousands of vacuum circuit breakers manufactured every year. However the vacuum interrupters and switches which form the heart of the equipment are sealed for life devices which have a calculated vacuum life of 20 years from seal off regardless of usage. In service the equipment has proven extremely reliable over this period, so reliable in fact that there are many thousands of interrupters still in service which are 30, 35, or even 40 years old! This in turn raises a problem. How to verify the integrity of the vacuum insulation within the sealed devices.

The paper discusses this background, together with the excellent experience gained over more than 30 years of field experience, the causes of the rare failures in service, and the effect of ageing, then moves on to discuss the different techniques used in manufacture and in service for assessing the state of the vacuum insulation, together with their advantages and disadvantages. The particular difficulties raised due to the unique properties of vacuum insulation are also discussed, including the Paschen curve and its relation to vacuum condition and life prediction.

INTRODUCTION:

Vacuum interrupters are sealed vacuum devices which form the key interrupting component in High Voltage electrical switchgear for voltages up to 40.5kV. They use the superb dielectric properties of vacuum coupled with arcs physics in vacuum to interrupt currents from a few amps up to many kA. A typical vacuum interrupter is shown in Figure 1.

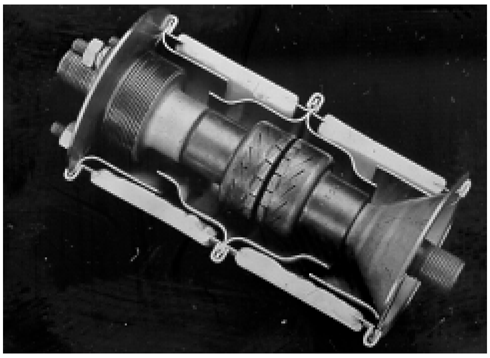

Figure 1. A sectioned vacuum interrupter rated at 12kV: 25kA; 1250A

Vacuum interrupters and switches are sealed vacuum devices. This means that they are pumped down to a suitable level of vacuum and then sealed off, and that after sealing there is no further significant active pumping. They rely on their hermetic sealing to maintain the appropriate vacuum level for operation.

As sealed devices they are subject to a number of factors which can significantly affect the level of vacuum. These fall into two main types, Real leaks and Virtual leaks. But before we discuss these it is necessary to establish what level of vacuum is necessary for the correct operation of these devices, and also what the consequence of losing vacuum is.

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 and quality control methods employed in manufacture together with careful design means 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, and in this case failure could be catastrophic. After losing vacuum it is likely that a closed vacuum interrupter would continue to function correctly for some time without any apparent problem. However if the switchgear were then operated and tried to commutate a short circuit current the failure would be catastrophic, resulting at the very least in total destruction of the interrupter and possibly the switchgear. To minimise the possibility of this occurrence, the key question is how can the condition of the vacuum insulation be verified and most importantly given a prediction of further service life?

DISCUSSION:

The Sealed for Life Concept

In the 1960’s HV 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. However for any sealed for life device, the period of life must be defined, and this was originally set at 20 years which was normal for a vacuum tube, and is now the industry standard. As the overall switchgear has a nominal life of 40 years, it was assumed that the Vacuum Interrupters would be replaced after 20 years in a mid-life service for the switchgear.

However since the 1960's the world of switchgear has changed beyond recognition, with privatisation of the utilities on one side, and a rationalisation of the switchgear manufacturers on the other. As part of this change users of the 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 Effect of Vacuum Level on Performance

The vacuum insulation is fundamental to the operation of vacuum interrupters, and it is necessary to explain what we mean by vacuum, and the effect of loss of vacuum on performance. The design of vacuum interrupters has been described in detail elsewhere [2], but a brief description here is necessary for understanding.

Vacuum Interrupters are sealed for life vacuum devices which perform current interruption at the next available current zero once the contacts have been separated. 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.

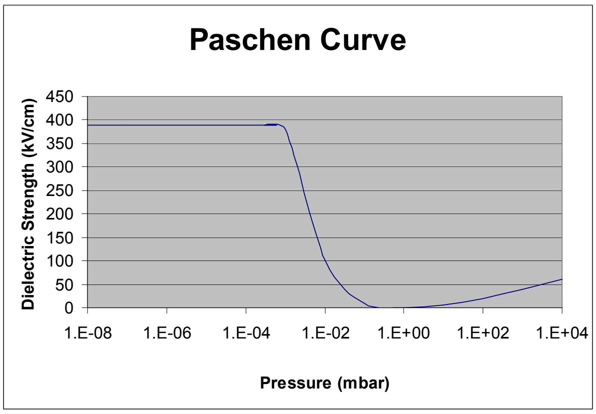

Figure 2: The Paschen Curve.

Electrical insulation in vacuum follows the Paschen curve shown in Figure 2. Normally for gaseous insulation we are concerned with the right hand side of the curve, showing increasing dielectric strength for a gas with increasing pressure. However for vacuum we are interested in the left hand part of the curve where, as can be seen, the dielectric strength suddenly improves after a minimum of ~ 1 mbar, to a very high level at around 10^{-3} mbar, after which it remains effectively constant. This is an important effect, as it means that any pressure better than 10^{-3} mbar has no effect on the dielectric strength of the vacuum gap. Which in turn means that any change in pressure which remains lower than 10^{-3} mbar will have no effect on the performance of the vacuum interrupter or switch. This is termed the "Limiting Value" and is how we define vacuum for these devices.

Vacuum Life Assessment

For a vacuum interrupter or switch the actual pressure in the device is not important. What is important is that the pressure does not increase to more than the Limiting Value, below this level there are too few gas molecules to affect the dielectric strength of the contact gap or the interruption process. Therefore "Sealed for Life" actually means that the pressure in the device will not increase to higher than the Limiting Value within the stated life of the device.

The manufacturing process and quality procedures for vacuum interrupters and switches are set around the life of the devices which as an industry standard is 20 years (normally termed Storage Life in the industry). This life is from the date of seal off, and is not affected by use, switching operations, or short circuit operations. Vacuum within the interrupter can be degraded due to gas entering from outside, termed a "Real" leak, or from out gassing from within the interrupter termed a "Virtual" leak. We are interested in the pressure rise, not how it is caused, and so to verify the apparent leak rate of an interrupter we must use a technique which includes both types of leak.

Manufacturers verify that each interrupter will meet this requirement by means of a simple calculation. This requires measuring the actual pressure within each device twice after seal off, and extrapolating the effective leak rate to show that the pressure will not reach the Limiting Value within the 20 year life. This is shown in Figure 3.

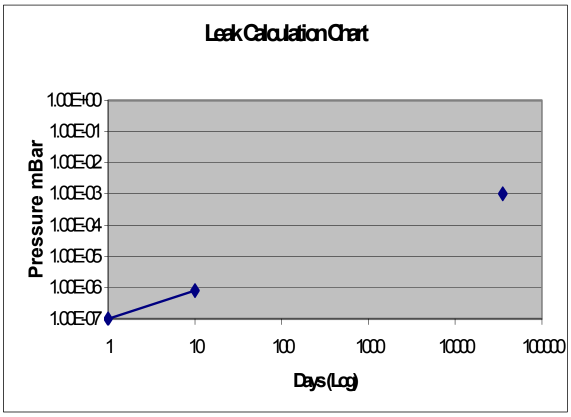

Figure 3: Leak Calculation Chart for a Vacuum Interrupter.

The pressure scale is of course logarithmic, and for simplicity time in days is also shown logarithmically, giving a straight line for a linear leak. This is because although the scale is logarithmic, an actual leak consists of so many gas molecules per second which is a linear effect. Meaning that to change from 10^{-7}mbar to 10^{-6}mbar may take 10 days, to then go from 10^{-6}mbar to 10-5mbar will take 100 days and so on. This effect allows manufacturers to store the interrupters for only a week or so to determine the leak rate over 20 years. This is a worst case calculation as most if not all of the gas will be produced by out gassing of internal components, the rate of which will normally decrease with time.

As may be appreciated, this whole system relies on accurately measuring the level of vacuum within the sealed device.. Normal vacuum gauges are too fragile and not suitable for incorporating in Vacuum Interrupters. But fortunately the geometry of these devices can be designed to mimic a particular type of vacuum gauge, which was invented in the 1940's and is eminently suitable for measuring these low pressures accurately [3].

Pressure Measurement

The Penning & Inverse Magnetron Methods
The trick is to use the vacuum interrupter as its own gauge. The principle is that of a crossed field discharge where a high voltage is applied to electrodes within vacuum at 90' to a large magnetic field [4]. The original Penning configuration is shown in Figure 4.

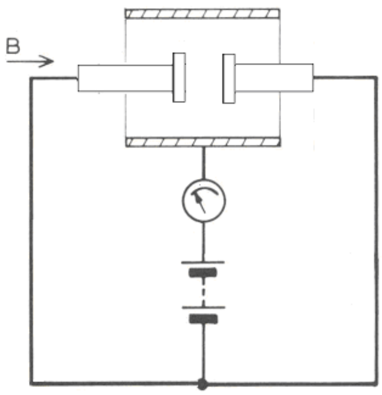

Figure 4: Vacuum Interrupter as a Penning Gauge.

This is where two electrodes at one potential are surrounded by a cylindrical electrode at the other potential. Electrons move from the Cathode to the Anode in a helical orbit ionising gas molecules. The current which flows is proportional to the number of gas molecules ionised within the gap, which gives a reading of pressure. By comparing Figure 4 with Figure 1, it can be seen how the geometry of a vacuum interrupter lends itself to this method.

An alternative, more sophisticated method, is the Inverse Magnetron Discharge, shown in Figure 5.

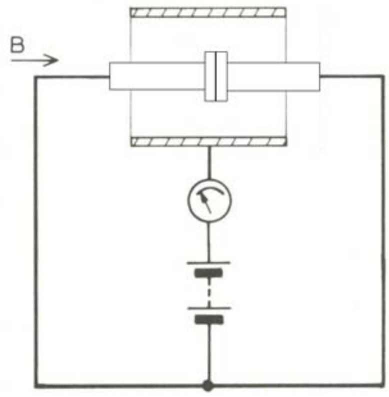

Figure 5. Inverse Magnetron Method of Pressure Measurement.

These techniques are well proven and can give very reliable measurement of vacuum within the sealed devices, although they must be carefully calibrated for each Vacuum Interrupter type. Figure 6 shows an industrial Vacuum Interrupter Pressure Measuring Machine using these principles.

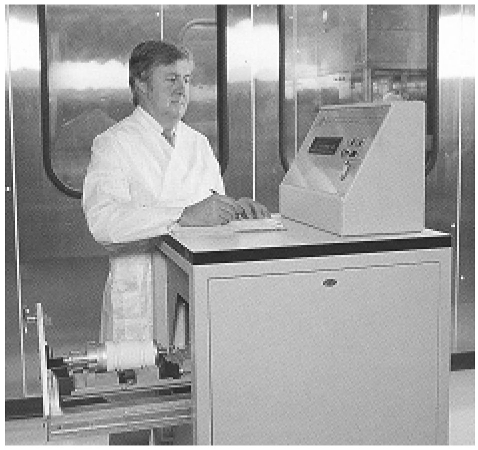

Figure 6. Vacuum Interrupter Pressure Measuring Machine in use at Vacuum Interrupters South Africa Limited.

Service Experience
Since the 1970's when vacuum interrupters were first shipped in large quantities we have seen this technology dominate the Medium Voltage primary switchgear market worldwide. Today there are literally millions of vacuum interrupters in service, with many thousands at or over 20 years old. Generally the experience has been excellent with failure of the vacuum insulation very rare. The overall MTTF of vacuum interrupters in service for many manufacturers being better than 40,000 interrupter years. However there have been small numbers of failures over the period. These can be categorised into three types.

1. Mechanical damage. This is probably the main case of failure and is due to bad handling of the interrupters during transport, assembly or more rarely in service. The stainless steel bellows are particularly vulnerable to abuse, and in some designs are a source of weakness. This type of failure tends to result in failure in the early years of operation.

2. Corrosion: This is an age related affect and is potentially the main issue when dealing with older vacuum interrupters. The materials used in the construction of vacuum interrupters, stainless steels, ceramics, copper, are generally corrosion resistant. However in certain environments they may be susceptible to attack. This may be due to the service environment, or for example to the use of corrosive cleaning materials. This tends to occur in later years, but cases have been seen where corrosion failures occurred very quickly under special circumstances.

3. Design issues: Not all vacuum interrupters are the same. Depending on the manufacturer they not only differ in contact materials, arc control systems, and other fundamental aspects of the design, but they also differ in the manufacturing methods used and specific materials. This has led to a number of interrupter failures in the past, some of which were due to corrosion from the manufacturing process or by contamination sealed within the interrupter.

To emphasise, the actual numbers of vacuum failures of interrupters in service has been extremely small, but they do happen from time to time.

Vacuum Testing methods
As it is not practical to put gauges on the interrupters themselves, and Vacuum Interrupter Pressure Measuring machines are very expensive and not usable on site, the vacuum insulation is tested when in service using a simple voltage check. For air, provided that the voltage is high enough, this shows that the interrupter is on the left side of the Paschen curve, and should function correctly. However, it cannot predict the future state, and it is possible that the interrupter could reach a dangerous pressure immediately after the test. The voltage test only allows you to detect an interrupter in which the vacuum insulation has already failed.

As the interrupters themselves together with the manufacturer's quality system are focused on a 20 year vacuum life (normally termed Storage Life in the industry), it is reasonable to say that this voltage test is sufficient to verify performance. The manufacturer will have performed tests during the development stage of the interrupter to verify its storage life, mechanical strength and corrosion life for the predicted Storage Life of the vacuum insulation.

Life after 20 years
However, after 20 years the situation changes. Once the twenty years is completed the device moves outside of the known and calculated results of the manufacturers tests. This means that the integrity of the vacuum insulation can no longer be relied upon. It does not mean that immediately after 20 years that the interrupters will lose vacuum. What it does mean is that as the device moves further from the 20 year storage life limit, it becomes less possible to guarantee the integrity of the vacuum insulation.

Eventually for all devices one of the failure modes will occur, and the device will eventually fail. This may be many years in the future, or shortly after the 20 year storage life has been exceeded, even the manufacturer cannot predict this. The only guarantee is that if the devices are kept in service long enough, they will eventually fail.

CONCLUSIONS:

Vacuum Interrupters are a key component in the electrical distribution system. They have a design Storage life for the vacuum insulation of 20 years, and within this period have given exceptional levels of reliability. However, after twenty years the devices are outside of the manufacturers design and quality assurance system. In addition, the normal tests to verify the vacuum insulation performed by the user are inadequate as a means to prolong service life as they can only detect a device which has already failed.

Due to ageing effects the interrupters will eventually lose vacuum. Many interrupters are capable of continuing in service for many years more than the 20 year Storage life originally assigned, however a number will start to fail relatively early, and unless a reliable means of checking the pressure and leak rate of each interrupter is used, it is not possible to find these interrupters which are prone to early failure. The existing voltage based insulation checks are just not suitable for this. However if a suitable technique were developed then it would be possible to prolong the Storage Life of the vast majority of vacuum interrupters significantly, while detecting those which are showing signs of future failure.

It is possible for individual vacuum interrupters to remain functional for a very long time. Figure 6 shows the world's first split Contrate prototype vacuum interrupter which was sealed off in the early 1960's and still has good vacuum almost 50 years later. It is presently in the Science Museum, London.

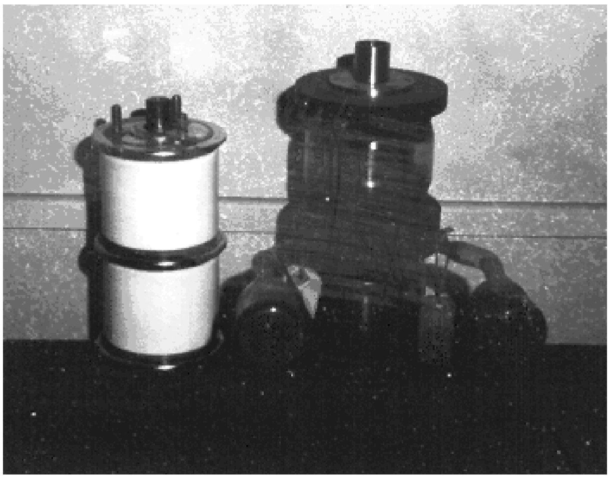

Figure 7: The World's First Split Contrate vacuum interrupter (right), now almost 50 years old.

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AUTHOR BIOGRAPHY:

Leslie T Falkingham was born in Leeds, England, in 1955. He was made a Fellow of the Institution of Electrical Engineers (IEE) in 1988 and a Fellow of the Institution of Mechanical Engineers (IMechE) in 1987. He is a Chartered Engineer in the UK (C.Eng) and is also a European Engineer (Eur.Ing).

He graduated from Lanchester Polytechnic, Coventry, England, in 1978 with BSc (Hons) in Combined Electrical and Mechanical Engineering, and obtained his PhD from Cranfield University (UK) in 2002. He has been a visiting Fellow of the University for a number of years. He is a member of the Permanent International Scientific Committee of the International Symposium for Discharges and Electrical Insulation in Vacuum (ISDEIV) and a member of the Current Zero Club.

His employment experience includes; Over ten years at Vacuum Interrupters Limited, London, England where he performed R&D, and designed and developed vacuum interrupters, Two years with GEC South Africa where he designed and built a new factory to manufacture vacuum interrupters, and ten years as Technical Director of GEC Alsthom Rugby where he built up and then led the ALSTOM Centre of Excellence for Vacuum Switching Technology. In addition he has been heavily involved with the ALSTOM vacuum interrupter plant in Calcutta, India. He has spent most of his working life involved in the design, development, and manufacture of vacuum interrupters and switches and their application in medium voltage vacuum switchgear. He holds a number of patents, and is an acknowledged expert internationally in this field. During his career he has produced papers and presented lectures on the technology world-wide. From 2001 he was Technology Director for ALSTOM T&D Medium Voltage Business, and then from 2003 Technology Director for AREVA T&D Products based in the head office, Paris, France. In August 2005 he reformed Vacuum Interrupters Limited in the UK where he is presently Managing Director.

His special fields of interest include: All aspects of vacuum interrupter and vacuum switchgear design & manufacture; R&D Management & Strategy and in particular the optimisation of industrial R&D.

He received the Nelson Gold Medal from GEC 1n 1997 for "outstanding technical innovation", and the J.J. Thomson Medal of the IEE in 2002 for his "distinguished contribution to electronic engineering".