Predicting the Remaining Life of Vacuum Interrupters in the Field

Applying the Magnetron Atmosphere Condition Assessment (MAC) test in a field environment

INTRODUCTION

Historical perspective

Historically, air-magnetic and oil interrupters were the only types of interrupters used on circuit breakers rated at 2.4 kV and higher. The air interrupters predominated the lower voltages in this range – from 2.4 kV up to 25 kV. Above 25 kV, oil interrupters were the more commonly used primarily because of their ability to interrupt higher arc energies.

Air-magnetic interrupters

Air-magnetic interrupters degrade somewhat each time they are opened under load, and they degrade significantly if they are interrupted under fault. The contacts can be repaired or replaced if required; however, the maintenance of these types of circuit breakers was not always properly scheduled sometimes resulting in failures.

In addition to the maintenance problem, the arc-chutes are very large and heavy. Some of the arc chutes on these breakers are also somewhat fragile and can be broken if not properly handled.

Oil interrupters

Oil interrupters are also very heavy. More importantly, the interrupter itself is submerged in oil and is difficult to reach for inspection. Testing methods such as contact micro-ohmmeter tests, insulation resistance tests, power factor tests, and the like are quite reliable in determining the condition of the interrupter. However, like air-magnetic interrupters, these units were not always maintained as they should be.

In addition to maintenance and size problems, stricter environmental requirements make using these types of interrupters subject to increased regulation and higher cost of maintenance.

What accounts for the amazing popularity of the vacuum interrupter?

Partially as a response to many of the issues with air-magnetic and oil interrupters, widespread use of vacuum interrupter (VI) technology and SF-6 technology in electric power distribution systems started over thirty years ago. In the intervening years, the VI has become the choice for the vast majority of circuit breakers applied between 1000 volts and 36,000 volts.

Figure 1. External view of a typical vacuum interrupter.

The VI (See Figures 1 and 2) is light-weight, sealed from the atmosphere, and has a very long predicted useful life. Since VI technology was first used in the industry, typical predictions have been 20 or 30 years.

Thus there are a number of features that have led to its wide acceptance as a superior interrupting technology. These features include the following:

- It is a relatively compact and sealed unit.

- The travel required to open is very short with distances that vary with age and manufacturer. The actual travel distance varies with VI geometry and voltage level; however, typical distances range from approximately 8 mm (0.314 in) to 12 mm (0.472 in).

- It has the longest expected service life of any interrupting method.

- When a VI experiences one of their relatively rare failures, the resulting damage is sometimes much less than air-magnetic interrupters. However, they still can fail spectacularly causing great damage.
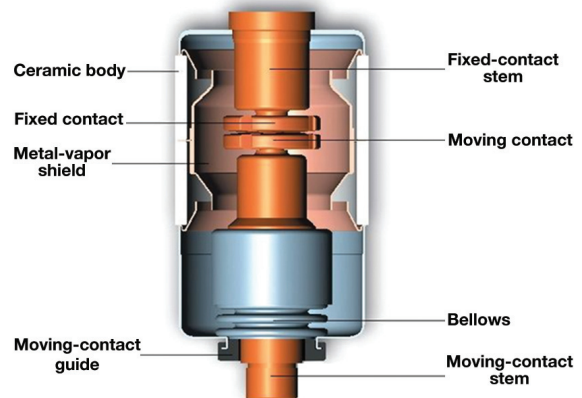
Figure 2. Internal view of a typical vacuum interrupter.

Why do vacuum interrupters work?

The VI's high interrupting capacity is based on the physical principle discovered by Louis Karl Heinrich Friedrich Paschen (1865-1947). Paschen did original experimental research and discovered that the dielectric strength of a gas is a function of the gas pressure (p), the distance between the two electrodes (d), and the type of gas. This relationship is given in Equation 1.

$$V = \frac{apd}{\ln(pd) + b}$$

Paschen's Equation 1.

Note that a and b are constants that are derived for dry air.
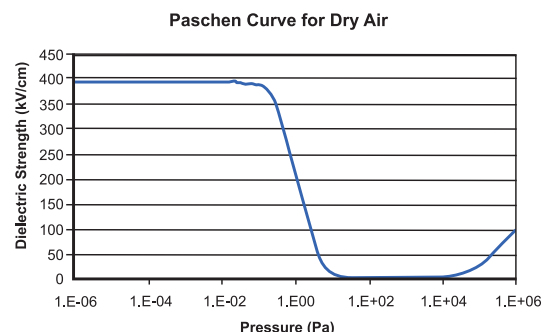
Paschen Curve for Dry Air

Figure 3. Paschen's curve for dry air.

Figure 3 is taken from a paper presented by Falkingham and Reeves[i]. This shows that the dielectric strength of air starts to increase dramatically as the air pressure drops below approximately 10 Pa (10^{-1} millibar)[1]. It continues to rise swiftly until pressure reaches approximately 10^{-1} Pa (10^{-3} millibar), and then remains fairly steady at slightly less than 400 kV/cm (approximately 1000 kV/in).

This means that the typical contact gaps (8 mm to 12 mm) will have dielectric strengths between 320 kV and 1200 kV or higher for vacuum levels between 10^{-1} Pa and 10^{-6} Pa. The interrupting capacity in a VI will vary depending on contact design, contact separation and vacuum level. The contact design and separation are design features for any given VI. However, we have shown that the interrupting ability will be very high and very sensitive to the pressure (vacuum) level inside the VI.

VACUUM INTERRUPTERS: THE PROMISE

VI useful life projections
As might be expected, the primary basis for the wide acceptance of vacuum interrupters is financial. Consider that VIs offer vastly longer life and greatly reduced maintenance costs when compared to air-magnetic and oil interrupters. Their life span/number of operations specifications are up to 10 times those of the older technologies and the useful life of the VI may be up to fifty percent (50%) greater than SF-6 interrupters. At least part of the reason that VIs are so long-lived is because of their simple, yet rugged construction.

VI Construction
The following discussion provides a very brief overview of the construction of the VI. Understanding this information will help the reader to better understand the later discussion about the maintenance problems associated with the VI, and provide the basis to analyze the value of the new field test which will be presented. The following descriptions refer to Figure 2.

Contact Mechanism
The contact structure comprises two parts – the moving contact assembly and the fixed contact assembly. The fixed contact is stationary, held firmly in place, while the moving contact is free to move. When the circuit breaker operates the moving-contact stem moves the contact and compresses (open) or decompresses (closed) the bellows. The bellows system provides a much more secure seal than a bushing gasket.

Metal-vapor shield
The metal-vapor shield has three critically important purposes. The following information is paraphrased from *The Vacuum Interrupter: Theory, Design, and Application* by Paul G. Slade.[ii]

1. It captures the metal vapor created by the metallic arcing that occurs when the contacts open. The metal vapor is highly ionized and, in addition to the thermal expansion, is drawn to the vapor shield by electrostatic force. When the vapor contacts the shield, it quickly solidifies and adheres to the shield. This helps to maintain the vacuum level inside the VI.

2. The metallic vapor shield also serves to keep the electrostatic field uniformly distributed both inside and outside the VI.

3. It protects the ceramic body from the high levels of radiation during arcing and interruption, and prevents any high level arcs from directly contacting the ceramic body.

Ceramic Body
Porcelain-ceramic has become the predominant material for the body of the VI. The characteristics that have made it the material of choice include high strength, good dielectric strength, the ability to withstand very high temperatures, impermeability to helium (He) and extremely low permeability to hydrogen (H_2), and the ability to form very tight seals with brazed metal connections such as the bellows, metal-vapor shield, and the fixed contact stem.

While all of these are very important characteristics, tight seals and low permeability are arguably the most important with respect to the long life of a VI. As discussed before in this paper, the vacuum level is the key to the proper operation of a VI.

VI factory tests
The following tests are among those that are most commonly applied by manufacturers when a VI is manufactured and/or when it ships to a customer. The coverage is not exhaustive; however each test and its importance will be explained in enough detail to allow understanding of the remaining parts of the paper.

These tests may be performed on an entire batch of new VIs, or – more commonly – on a statistically significant sampling taken from the new batch. The three that are discussed are ones that are related directly to the service life of the VI.

Contact Resistance test
A micro-ohmmeter is applied to the closed contacts of the VI and the resistance is measured and recorded. The result is compared to the design and/or the average values for the other VIs in the same run.

High potential testing
A high potential voltage is applied across the open contacts of the VI. The voltage is increased to the test value and any leakage current is measured. Factory testing may be done with either AC or DC high-potential test sets. DC is less commonly used because high, DC voltages can generate x-rays when they are applied across a vacuum contact.
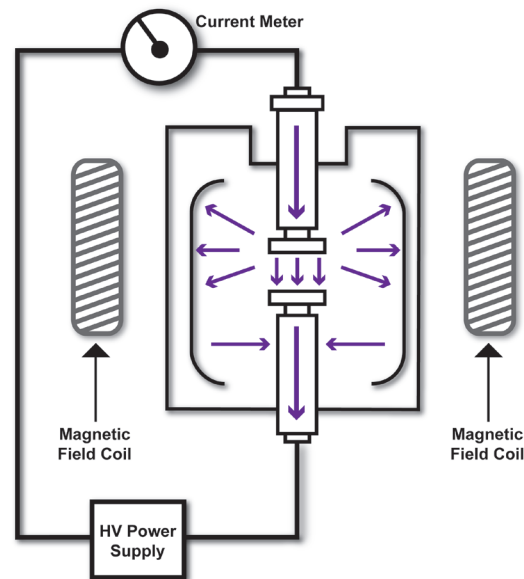
The leak-rate test (MAC test)

Figure 4. Vacuum level test using the Penning Discharge Principle.

This test is based on the Penning Discharge Principle which is named after Frans Michael Penning (1894-1953). Penning showed that when a high voltage is applied to open contacts in a gas and the contact structure is surrounded with a magnetic field, the amount of current flow between the plates is a function of the gas pressure, the applied voltage, and the magnetic field strength.

Figure 4 shows a diagram of the test set up used for the leak rate test. A magnetic field is set up by placing the VI into a field coil. The field is created by a direct current and remains constant during the test. A constant DC voltage, usually 10 kV, is applied to the open contacts, and the current flow through the VI is measured.

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[1] For those of you who are still more attuned to English units of measure, 1 atmosphere is approximately 14.7 psi (101 kPa)

Since the magnetic field (DC) and the applied voltage (DC) are both known, the only variable remaining is the pressure of the gas. If the relationship between the gas pressure and the current flow is known, the internal pressure can be calculated based on the amount of current flow.

The factory leak-rate test procedure is as follows:

1. The internal pressure is determined as described in the preceding paragraphs.[2]
2. The VI is placed in storage for a period of time – usually a minimum of several weeks.
3. The VI's internal pressure is tested again. This test is sensitive enough that even in that short time a very tiny change will be observed.
4. Using the difference between the two test pressures, a leak rate versus time curve is developed.

Referring to Figure 3, we see that if the pressure falls below 10^{-2} Pa, the dielectric strength – and thus the interrupting capability – will deteriorate rapidly. The calculated number of years required for the pressure to reach 10^{-2} Pa will indicate the expected service life of the VI.

VACUUM INTERRUPTERS IN THE FIELD
Although vacuum interrupters are very long-lived, they have a useful service life just like any piece of equipment. The projected life of a VI, as determined by the factory leak-rate test assumes a constant leakage rate throughout the life of the VI; an assumption that may not be valid for any given interrupter. Also consider that if not properly maintained all equipment will fail eventually. VIs are no exception to this truth.

Failure Modes
There are several possible types of VI failure.

1. The most common failure occurs when a VI reaches its wear limits. The VI has a set of soft copper alloy contacts that are mechanically shocked every time the breaker is opened and closed. When no current flows, the damage to the contacts is caused primarily by mechanical shock. Every time it is opened under load, overload or fault current, some of the contact material is lost to metal vapor and re-deposited other places in the VI canister – hopefully, but not always, on the metal-vapor shield.

2. Another common failure is internal arc flashover caused by metal vapor and sputtering material being deposited on the inside of the canister. This is especially bad if the material is deposited on the inside of the ceramic shell as it greatly reduces the insulation quality of the shell. Since the shell must be able to withstand the recovery voltage caused by an arc interruption, insulation failure of the shell can cause a catastrophic mechanical failure of the VI.

3. Loss of vacuum due to mechanical failure of the bellows, pinch tube or a manufacturing defect. This type of failure is quite often related to the number of operations multiplied by the number one killer on any VI – torsion exerted on the bellows. Even one degree of torsion on the bellows can reduce the number of operations by a factor of 10. This torsion can be caused by improper installation either at the factory or re-installation during an overhaul. Wear on the breaker mechanism during operations can also introduce torsion.

4. Last is the loss of vacuum due to leak rate. The leak rate was checked at the factory and is determined generally to exceed 20 or even 30 years; however, the leak rate can be greatly increased by improper installation, failure of components, or damage during maintenance procedures. Recent field experience has an increasing number of low pressure and dead in the box new VI in manufactured VCBs recently.

Of course, life extension and failure prevention can both be dramatically improved by proper maintenance.

The problem
Of the three factory tests discussed in this paper, only two have been used in the field – the contact resistance test, and the high-potential test. Neither of these is able to provide a value for the vacuum pressure inside the VI. Even the high-potential test is a go/no-go result. Even using a DC high-potential test set will not give predictable results that can be used. The DC high-potential test results may show a gradual increase over time, but it is not sufficient to determine when, or if, the gas pressure has dropped to critical levels. At least – not until the interrupter fails.

As previously noted, the pressure inside a VI will increase with time. There will always be some leakage in even the best made VI. That leakage may be slow enough that the VI will meet or even exceed the manufacturer predicted service life. On the other hand unexpected increases in the leakage rate can greatly shorten its life. As described in the previous paragraph none of the classic field tests can effectively evaluate the condition of the vacuum inside the VI.
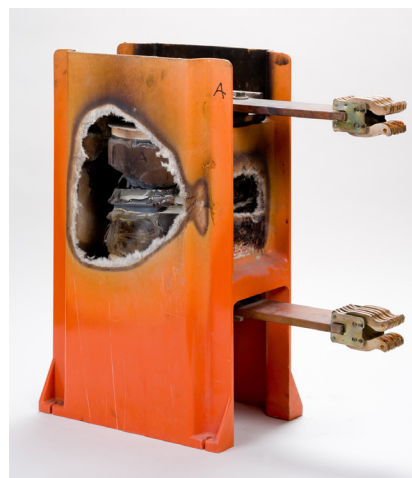

Figure 5. Failed vacuum interrupter.

Many VIs have been in service for twenty, thirty, or more years. A huge percentage of them are well past the manufacturers' predicted life. Figure 6 shows a failed pole assembly. This failure occurred fairly recently. Industry studies are showing that an increasing numbers of such failures are occurring.

It cannot be stated to a 100% certainty that the proximate or root cause of the failure shown in Figure 5 was insufficient vacuum. However, it can be stated to a high degree of certainty that had the vacuum pressure been in the acceptable range of 10^{-2} Pa to 10^{-6} Pa, the bottle would not have failed.

Based on old technology, a new field test is being used successfully to measure the vacuum pressure with a field test.

A PREDICTIVE FIELD TEST FOR VI PRESSURE
Roadblocks and solutions
The test equipment that is used to test vacuum in a VI is called a magnetron. Both technical and logistical problems have prevented the use of the magnetron in the field. The five major problems are as follows:

- The magnetron and its associated equipment have been too bulky to be used in the field.
- Existing magnetrons have been very touchy about keeping their calibration when moved.
- The available coils used to create the magnetic field could not be used in the field.
- There were few VIs that had graphs showing the relationship between ionization current and (vacuum) pressure.
- The trending and prediction tools available for evaluating such a test were not available.

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[2] The machine used to generate the magnetic field is called a *magnetron*. It is described briefly later in this paper.

However, this has changed with the introduction of new technology that has been researched and developed extensively over the last five years.

Magnetrons suitable for field and shop use

With industry improvements in components and manufacturing capability, magnetrons such as that shown in Figure 6, are now coming onto the market for field use. It is small and portable and will retain calibration with only the normal procedures as specified in industry standards for field testing.

Figure 6. Portable magnetron suitable for field work

Application of the magnetic field to the VI

When tested in the factory or shop, the VI is inserted into a magnetic coil which is energized by the magnetron. Figure 7 shows a stand with an integrally mounted coil used for such testing. Although these types of coils can be used in the field, they are quite heavy and bulky, especially in the sizes required for some of the larger VIs. In addition to their weight, such a coil requires that the VI be removed from the breaker mechanism to be tested.

Figure 7. Stand mounted coil for application of uniform magnetic field.

Figure 8. A newly designed flexible magnetic field coil for field testing.

Figure 8 shows a flexible coil especially researched and designed for use in field testing. In this figure the technician had access to the VI itself and were able to apply the coil directly to it.

Figure 9. Flexible magnetic field coil applied to an entire pole.

Figure 9 shows how the flexible coil can be used on the entire pole when the VI is not readily available.

Placement of the flexible magnetic field coil cannot be arbitrary. Current studies and field test are underway to allow easy and accurate application of the coil.

Although many of the vacuum breakers in the field allow for application of the coil to either individual VIs or individual poles, some do not have sufficient space or configuration. Research on how to apply the coil to all three poles simultaneously is nearing completion.

Creating pressure versus current data

The relationship between the current flow through the vacuum and the gas pressure must be known before the magnetron can be used to calculate the pressure. There have not been many such graphs available to field personnel.

Figure 10 shows a test setup that can be used to develop the relationship between gas pressure and current flow. A VI is opened and a vacuum pump (red equipment on the left) is connected to it so that the pressure can be gradually decreased. The magnetron (not shown in this photo) is also connected to the VI. It applies the voltage and the magnetic field and records the resulting current for each different pressure point.

Figure 10. Test setup for developing vacuum versus current data.

The data collected may be saved to create graphs, tables, or even equations that express the relationship. The best way; however, is to let the magnetron do the job. After the information is collected it can be stored on the magnetron and each data set is correlated to its particular VI. When a field test is performed the operator tells the magnetron which VI is being tested. The magnetic field and the test voltage is applied, and the magnetron prints out the pressure that correlates to the resulting current flow.

Evaluating the data

Using the magnetron in the field allows the VI vacuum pressure to be tested every time there field testing is performed. The tested pressure value along with other relevant data is entered into a modern Condition Based Maintenance diagnostic and predictive Algorithm. (CBMA) The algorithm evaluates the results and develops a highly accurate evaluation of the current data to previous data and calculates expected future values for life prediction purposes.

This approach has been used very successfully to accurately analyze oil test results, insulation resistance results, and a host of other such tests. The initial results on predicting the expected vacuum pressures and expected service life are very promising.

Summary and Conclusion

- Even with their long life, VIs are starting to fail in greater numbers. In many if not most cases the VIs in the field have long exceeded their manufacturer-predicted life.

- Failures of the VI are often catastrophic with loss of the VCB, switchgear or worse.

- The 20 year manufacturer's original suggested life has generally been ignored by users. This has placed a large portion of the US industrial and utility distribution switchgear at risk of failure. Only through diligent testing and some luck can users expect no events to occur in the future. No one suggests that ignoring this possible failure is acceptable. And every VI will fail we just do not know when.

- Thousands of Medium Voltage Power Circuit Breakers have passed through service shops and the hands of credible testing companys only to be placed back in service. The only guarantee is that this device will function today. Many of these breakers were returned and the users felt they were assuring reliability till the next test or overhaul cycle, except this was not true. The VI actual pressure was unknown.

- Many of these have failed or will fail before the next scheduled maintenance cycle. This is a problem we have been working to solve for over 10 years.

Figure 11 illustrates the problem. Until now determining the remaining life of a Vacuum interrupter was like working on a puzzle for weeks only to determine the key piece was missing.

The following list summarizes what we have been doing and what data we have been gathering when maintenance is performed.

- Breaker Type
- VI part number and serial number
- Number of operations
- Operating environment
- Wear indication
- Contact resistance
- High-potential go/no-go test
- Circuit criticality

Clearly we have been missing a key part of the puzzle.

Although not yet in general use, the field test described in this paper has been tried and proven. Setting up for and performing the test is no more difficult that many of the field tests that we have become familiar with such as insulation testing, power factor, and partial discharge. The results are extremely accurate in determining both the vacuum level and in developing predictive data for the future. Some have even compared it favorably to the procedures that are routinely used for insulating liquid testing.

Additional research is ongoing, and we suspect that you will see a general deployment of this test over the coming years.

Remember all VIs will fail; it is only a matter of time. No assembled VI is impermeable; therefore, all have substantial leak rates. Will they fail when called upon to protect a critical load during a short circuit, or will they fail while in service and cause unexpected shutdown? When the test described in this article is employed, the possibility of such failures is greatly reduced.

[i] Leslie Falkingham and Richard Reeves, *Vacuum Life Assessment of a Sample of Long Service Vacuum Interrupters*, 20th International Conference on Electricity Distribution, Prague June 8-11, 2009, Paper# 0705.

[ii] Paul; G. Slade, *The Vacuum Interrupter: Theory, Design, and Application*, CRC Press 2008, Page 232.