PREDICTING THE REMAINING LIFE OF VACUUM INTERRUPTERS IN THE FIELD

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ABSTRACT

This paper introduces a recently researched and developed field test procedure used to determine the pressure inside a vacuum interrupter (VI). Basic concepts as well as case histories are included. Many in service VIs have reached or exceeded the projected useful life.

This new method allows the field test technician not only to determine vacuum level but also – by additional testing at one or more intervals – allow the prediction of remaining life. This test method uses field portable test equipment and a number of recently developed coils for applying a magnetic field to the bottle.

INTRODUCTION

For circuit protection application with voltages in excess of 1kV either air-magnetic or oil-based interrupters traditionally have been used. Over the last forty years vacuum interrupters (VI) or SF6 interrupters have supplanted the older technologies. For a number of reasons beyond the scope of this paper VIs are used in the majority of both new and retrofitted installations. Figure 1 is an external view of a typical, modern VI. Figure 2 is a rendering of the internal mechanism of a VI.

**A Typical Vacuum
Interrupter
Figure 1**
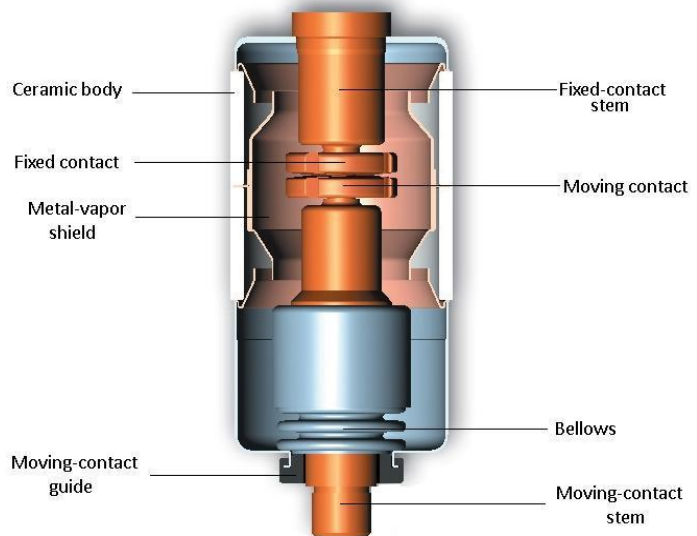
**VI Internal Mechanism
Figure 2**

VI manufacturers conduct a number of tests on their VIs before they ship them out. One of these tests – a leak-rate test -- has not been available to field personnel. The test set used by manufacturers is called a magnetron. Field portable magnetrons have not been readily available until recently.

HOW DOES A VI WORK

The VI's high interrupting capacity is based on: $V = \dfrac{apd}{\ln(pd)+b}$ $(Eq1)$

Where V is the breakdown voltage in Volts, P is the pressure in Atmospheres or Bar, and d is the gap distance in meters. The constants a and b depend upon the composition of the gas. For air at standard atmospheric pressure of 101 kPa, a= 4.36×10^7 V/(atm·m) and b= 12.8. The graph of this equation is the Paschen curve. By differentiating it with respect to pd and setting the derivative to zero, the minimum voltage can be found. This yields $pd=e^{1-b}$

This is a physical principle discovered by Louis Karl Heinrich Friedrich Paschen (1865-1947). Paschen did original experimental research and discovered that the dielectric strength (*V*) of a gas is a function of the gas pressure (*p*), the distance between the two electrodes (*d*), and the type of gas. Equation 1 shows this relationship. Note that *a* and *b* are constants that are derived for dry air. (For more information see reference [2].)
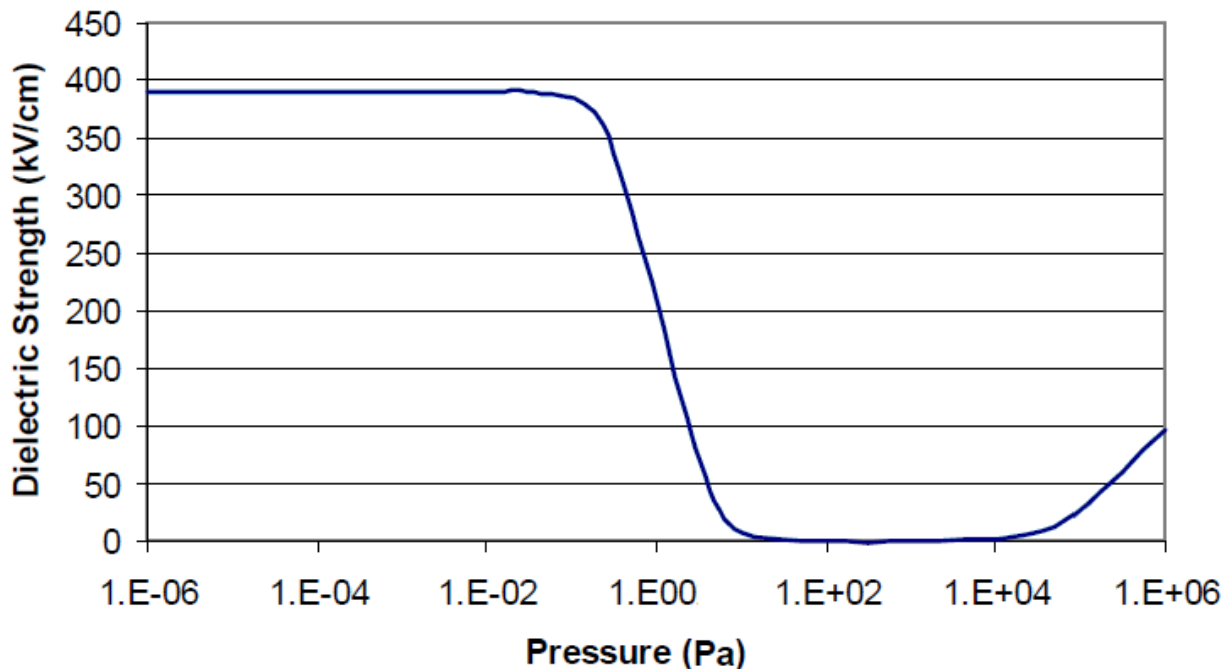
Paschen's Curve for Dry Air
Figure 3

Figure 3 is taken from a paper presented by Falkingham and Reeves.[1] It shows that the dielectric strength of air starts to increase dramatically as the air pressure drops below approximately 10 Pa (10-1 millibar). 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 (1.45 x 10^{-5} psi) and 10^{-6} Pa (1.45 x 10^{-10} psi).

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. Thus for any given VI will start to drop rapidly if the internal pressure rises above 10^{-2} Pa. Figure 4 shows an VI and its pole piece that have failed. Although there are other factors that can cause such a failure – loss of vacuum is a frequent contributor.


Failed Vacuum Interrupter Figure 4

THE VACUUM LEVEL TEST
ALSO REFERRED TO AS THE MAGNETRON ATMOSPHERIC CONDITION (MAC) TEST

Testing the vacuum level in a sealed, evacuated VI is based on the Penning Discharge Principle. It is named after its discoverer Frans Michel Penning (1894-1953). Penning showed that when a high voltage is applied to open contacts in a gas container and the contact structure is surrounded with a magnetic field, the amount of current (ion) flow between the plates is a function of the gas pressure, the applied voltage, and the magnetic field strength.

Figure 5 is a diagram of the vacuum level test. Placing the VI into a field coil sets up a magnetic field test. The field is created by a DC current and remains constant during the test. An evenly distributed, magnetic field density of 200 gauss (2 x 10^{-2} T) is required for consistent results. A constant DC voltage, usually 25 kV, is applied to the open contacts, and the current flow through the VI is measured.
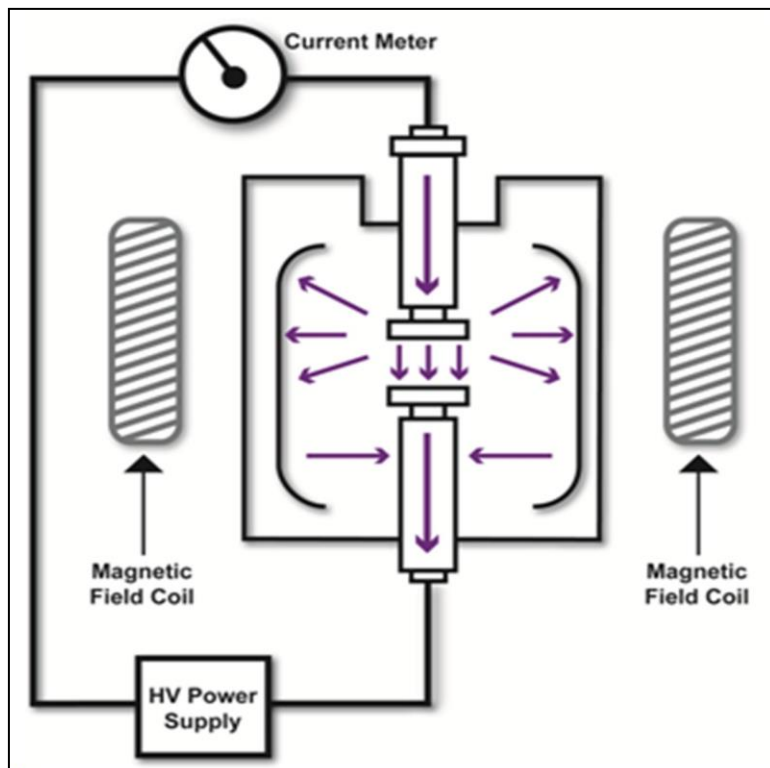
Both magnetic field and the applied voltage are direct voltages (DC) and are both known. The only variable remaining is the pressure of the gas. If the relationship between the gas pressure and the current flow is known, the internal pressure can be calculated based on the amount of current flow.

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

Diagram of the Vacuum Level Test Using a Magnetron Figure 5

FIELD TESTING

The test equipment that is used to test vacuum in a VI is called a magnetron. Previously both technical and logistical problems have prevented the use of the magnetron in the field. The major challenges have been as follows:

- The magnetron and its associated equipment have been too bulky to be used in the field.
- Laboratory magnetrons have been very sensitive and lose their calibration when moved.
- The available coils used to create the magnetic field could not be readily used in the field.
- There were few VIs that had graphs showing the relationship between ionization current and (vacuum) pressure.
- Advanced trending and prediction mathematical algorithms were not available.

With the new procedures and equipment that is available, the vacuum can now be tested in the field. Case Studies have proven that incipient failures can be predicted with this test. Figure 6 shows a portable magnetron connected to a VI via a flexible field coil. The magnetron is relatively small, portable, and will retain calibration with only the normal procedures specified in industry standards for field testing.
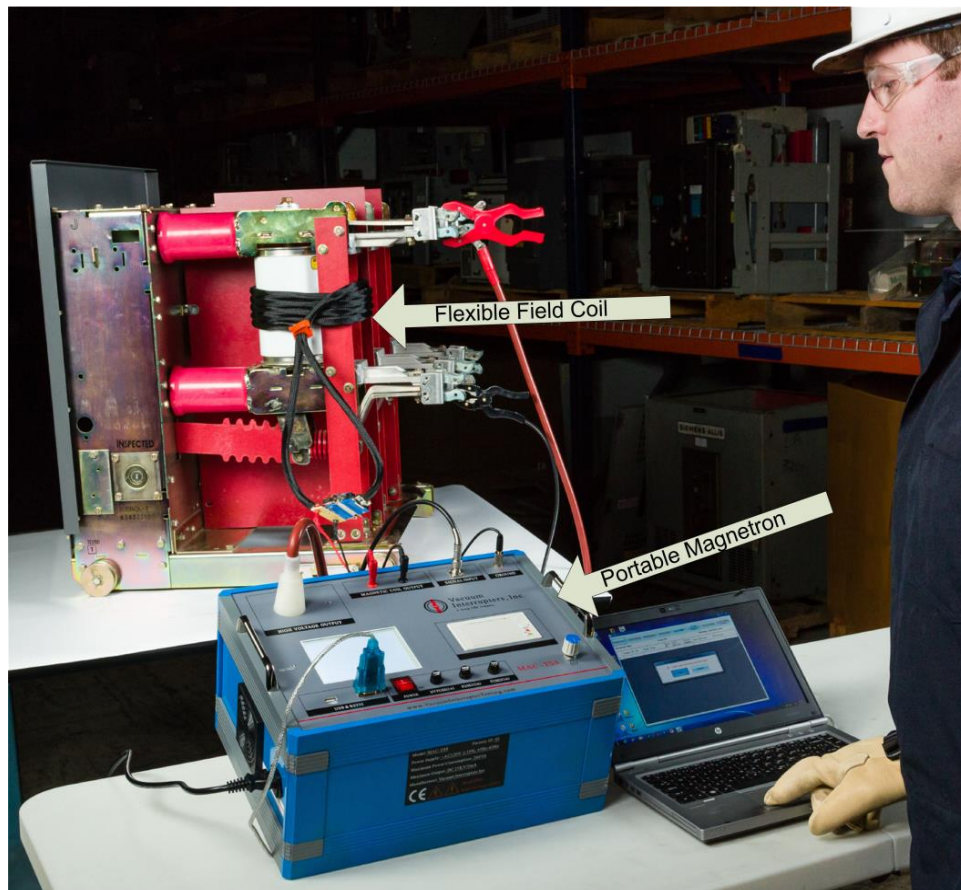
Testing a VI with the Flexible Magnetic Field Coil
Figure 6

APPLICATION OF THE MAGNETIC FIELD

The application of the magnetic field to a VI in the field is somewhat challenging. Figure 7 shows a laboratory test stand. The VI under test is inserted into the stand from the top. The magnetic field is created by energizing the stand's internal windings that surround the VI. This works well when access to the VI alone is possible.
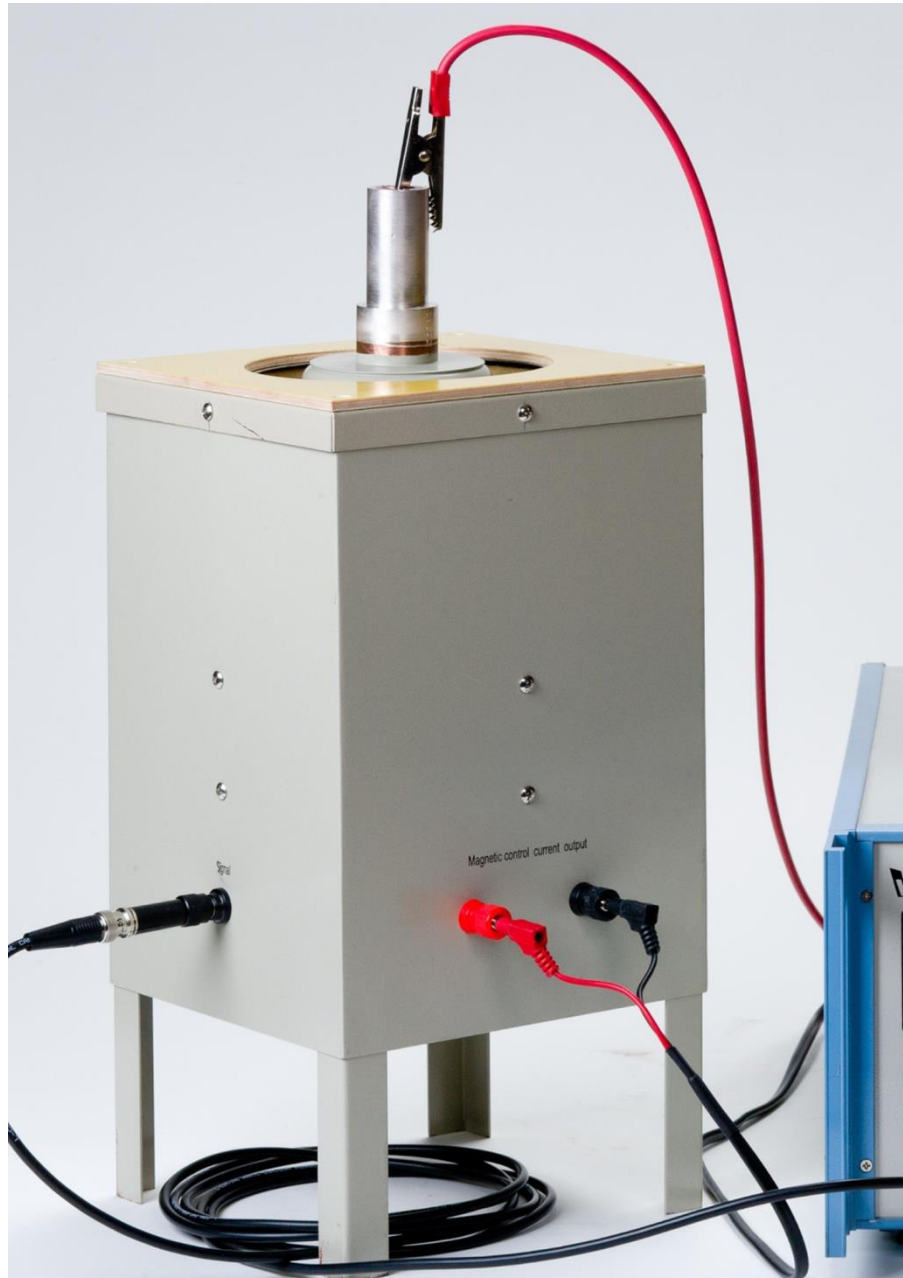
Test Stand Used to Vacuum Test VIs in the Laboratory
**Figure 7**

In the field or even in the shop it is sometimes difficult or impossible to remove the VI from the breaker and/or its pole-piece. Research has led to the development of different types of apparatus for application of the field when the VI cannot be removed easily. Figure 6 shows one of these pieces of equipment the flexible magnetic field coil. Figure 8 shows a close-up of another field test. Note that in Figure 6, the flexible magnetic field coil is wrapped around the pole piece as well as the VI.

Close Up of a Flexible Magnetic Field Coil in Use
Figure 8

CREATION OF PRESSURE VS CURRENT DATA

If the VI geometry, the high-voltage applied across the contacts, and the magnetic field strength are all constant, the vacuum level will be a function of the ionic current that flows with the VI is tested. During the research phase of this test method, the current vs. pressure curve was developed for each type of VI by using a test set up like the one shown in Figure 9.
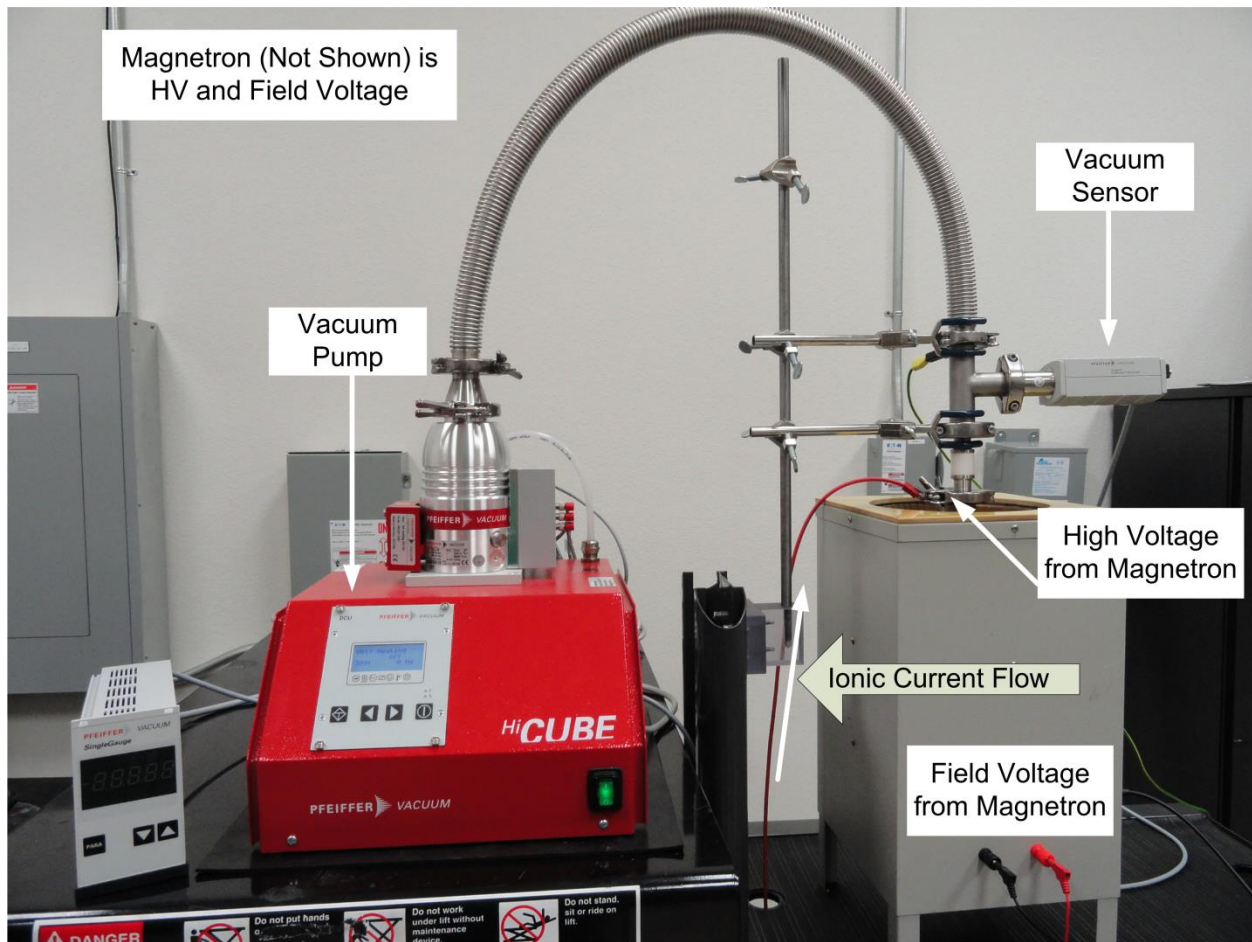
Test Setup to Determine Current vs. Pressure Curve

Curve Developed for Each Type of VI

The VI is first opened to relieve the vacuum and then inserted into a laboratory test stand. Then a vacuum pump and a pressure sensor are attached to the VI. A magnetron is used to apply the high-voltage across the contacts and the field voltage. (See Figure 5 for the electrical connection diagram.

The vacuum pump is started and ionic current readings are taken from the magnetron at several points during the evacuation period. The process is then repeated as the VI is allowed to re-pressurize.

Because of the large number of different manufacturers and models of VIs, developing individual curves for each vacuum interrupter is a huge task. Curves for a large number of the more common VIs have been developed and more are being developed. Specific curves for any VI can be developed on request.

VI Size vs. Vacuum Level

During the ongoing research, it was learned that the vacuum versus current relationship strongly correlates to the geometry of the VI. It has been seen that accuracies of ± 10% are realized when curves are developed solely on the basis of VI diameter. This relationship has allowed the development of individual generic curves that can be used for most vacuum interrupters in service today. This phenomenon has been verified by extensive testing using the laboratory setup shown in Figure 9.

EVALUATION CRITERIA

Prognosis of VIs and the breakers to which they are attached is not solely a function of the vacuum level. Based on extensive laboratory research and field Case Studies our researchers have developed a logical flowchart to determine what action an owner should take. Figure 10 shows the current version of that flowchart.
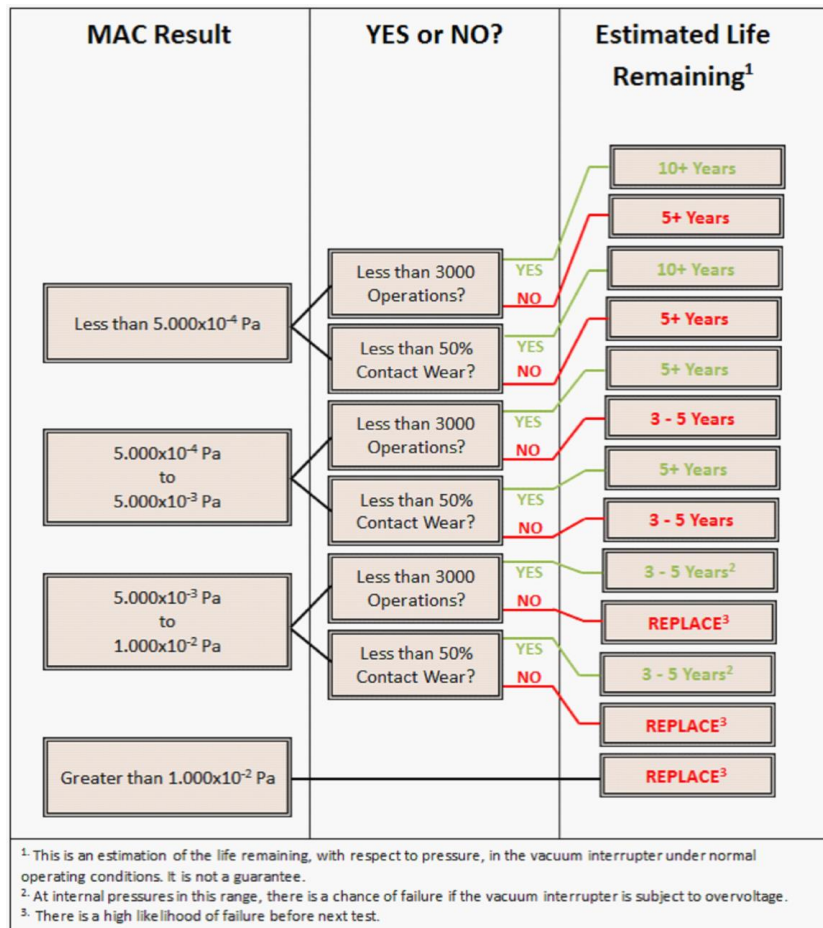
VI Evaluation Flowchart
Figure 10

CASE STUDY #1

During March 26 through March 28, 2012, field technicians from a qualified electrical testing firm performed field maintenance and testing on 60 vacuum circuit breakers at an electrical utility power plant. All of the breakers at this location were 25 years old or more. There had been two in-service failures in the months leading up to the service period.

All of the standard, field tests such as high-potential tests, contact resistance tests, and contact erosion were performed per ANSI/NETA MTS-2011. Based on a somewhat earlier version of the flowchart shown in Figure 10, the following results were obtained:

- Eight out of the sixty breakers were found to have a total of ten interrupters that required either immediate replacement or transfer to non-critical service.
- Two of the ten interrupters might have been flagged by contact wear alone; however, the other eight would not have been caught by the classical field tests.

If the vacuum level test (also called the Magnetron Atmospheric Condition or MAC test), eight circuit breakers that were in imminent danger of failure would have been put back into service.

CASE STUDY #2

In the latter part of 2013 a large wind farm built a new medium-voltage collection. A total of over 40 vacuum circuit breakers from 5 different manufacturers were installed. During the first year of service 5 vacuum interrupters failed. They were all from the same manufacturer.

The wind farm learned of the vacuum level test and called a NETA certified contractor to perform the test on all of the remaining breakers. The field tests of the remaining VIs found 5 more VIs with unacceptably high pressures. All of these were from the same manufacturer as the ones that had failed initially.

In summary:

- Over 40 Vacuum Breakers were tested.
- 5 additional VIs were found to have to have high pressure moving quickly toward failure.
- None of these would have been discovered with typical AC high potential go/no-go testing.
- Issue 1: Possible danger to operator and maintenance personnel.
- Issue 2: There would be more passive or catastrophic failures causing unexpected downtime.
- Issue 3: Equipment failures would not be picked up until a maintenance cycle outside of manufacturer's warranty.

CONCLUSION

As they reach the end of their predicted lives, 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.
The 20-year manufacturer's original suggested life has generally been ignored by users. This has placed a large portion of the U.S. 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 these possible failures 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 companies. When these breakers were returned to their owners, many thought that they were guaranteed to last until the next maintenance cycle. This is not true. When breakers are maintained and tested using traditional methods, they go back into service with only one guarantee: this device will function today.

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. The MAC test adds a new, extremely valuable tool to the field technician's kit.

The following list summarizes the data that field testers have gathered in the past:

- 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

As Figure 11 shows, we have been missing a critically important piece of the testing puzzle.

Magnetron testing in the laboratory has been proven itself for over 40 years and is a standard test for all VI manufacturers. Light, rugged magnetrons, innovative field application coils, and standardized results analysis allow this tested method of VI pressure analysis to be taken to the field. For three years it has been in regular use by dozens of testing companies and facility owners, and it t has been generally accepted by all that have applied it to their testing regimen.

The VI Maintenance Puzzle
Figure 11

Setting up and performing the test is no more difficult than 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.

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.

REFERENCES

[1] 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
 [2]Husain, E. and Nema, R.S, Analysis of Paschen Curves for air, N2 and SF6 Using the Townsend Breakdown Equation, IEEE Transactions on Electrical Insulation, Volume EI-17,August, 1982, pp 350-353

BIOGRAPHIES

John Cadick is a registered professional engineer and the founder and president of the Cadick Corporation. He has specialized for over 45 years in electrical engineering, maintenance, training, and management. Prior to creating Cadick Corporation, he held a number of technical and managerial positions with electric utilities, electrical testing companies, and consulting firms. In addition to his

consultation work in the electrical power industry, Mr. Cadick is the author of Cables and Wiring, DC Testing, AC Testing, and Semiconductors published by Delmar. He is also principal author of The Electrical Safety Handbook (published by McGraw Hill) and numerous professional articles and technical papers. Mr. Cadick has a BSEE from Rose-Hulman Institute of Technology and an MSE from Purdue University.

Finley Ledbetter, Group CBS, Inc. has worked in the field of power engineering for 30 years, including serving as an applications engineer and instructor for Multi-Amp. He was the founder of Shermco Engineering Services and Western Electrical Services, both NETA-accredited companies. Mr. Ledbetter is also the co-founder of Group CBS, Inc., which owns 12 circuit breaker service shops in the United States. He is a member of IEEE, a NETA Affiliate, and a charter member and past president of Professional Electrical Apparatus Recycler's League (PEARL).