Predicting the Remaining Life of Vacuum Interrupters in the Field

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Abstract

Vacuum interrupters have widely replaced older air-magnetic and oil interrupters for circuit breakers rated at 1 kV or higher and offer up to 10 times the expected lifetime than newer SF-6 gas interrupters. During manufacture, vacuum interrupters undergo contact-resistance, high-potential, and leak-rate tests. However, only the leak-rate test offers insight into the remaining lifetime of the vacuum interrupter. Leak-rate testing requires the use of a magnetron, which has prevented this test from being widely used in the field. New portable magnetron and vacuum-pump equipment now makes it possible to perform leak-rate tests in the field. This paper details a new predictive vacuum field test based on the leak-rate test that uses portable magnetrons and vacuum pumps, condition based maintenance algorithms, and both device-specific and generic vacuum interrupter current-vacuum curves that are based on vacuum pressures and device geometries.

Index Terms

circuit breaker, vacuum interrupter, air-magnetic interrupter, oil interrupter, field test, magnetron, condition based maintenance algorithm, predictive maintenance

Introduction

Circuit protection protects electrical service personnel, physical assets, and production schedules against shorts, faults, and dangerous arcing conditions. In addition to protecting equipment from power surges and sags that result in immediate equipment failure, circuit breakers, interrupters, and other protective devices also protect equipment from partial failures and faults that shorten the lifetime of electrical equipment.

For circuit protection application with voltages in excess of 1kV, electricians and maintenance personnel traditionally have used circuit breakers with either air-magnetic or oil-based interrupters. More recently, vacuum interrupters (VI) have supplanted many air-magnetic and oil-based interrupters because of their ability to interrupt power faster – improving equipment and personnel safety – for more cycles than older interrupters, which translates to longer lifetimes for circuit protection equipment and less cost to the user for replacement interrupters.

Figure 1: Vacuum Interrupter External View

VI manufacturers use three electrical tests to validate the operation of their products before sending them into the marketplace: contact-resistance, high-potential, and leak-rate testing. Of these three, only leak-rate testing provides results

beyond "pass/fail," which provides data for computerized maintenance management systems (CMMS) and enterprise asset management (EAM) systems. Leak-rate tests provide quantifiable data based on the internal pressure and vessel geometry that allows maintenance personnel to use predictive maintenance procedures and programs that result in higher equipment uptime and longer lifecycles compared to reactive maintenance programs.

However, until recently, leak-rate tests could not be conducted in the field because they required large, expensive magnetrons to generate magnetic fields that are necessary for leak-rate tests. New equipment such as portable magnetrons and condition based maintenance (CBM) algorithms detailed in this paper enable technicians to perform leak-rate tests in the field, generating quantifiable data that can be used as part of a predictive maintenance program.

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 to 15 kV and occasionally 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 are 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, and power factor tests are quite reliable in determining the condition of the interrupter. However, like air-magnetic interrupters, these units are 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.

Vacuum Interrupters

Partially as a response to many of the issues with air-magnetic and oil interrupters, widespread use of VI technology and SF-6 technology in electric power distribution systems started more than 30 years ago. In the intervening years, the VI has become the choice for the vast majority of circuit breakers applied between 1,000 volts and 36,000 volts.

The VI (See Figures 1 and 2) is lightweight, 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.
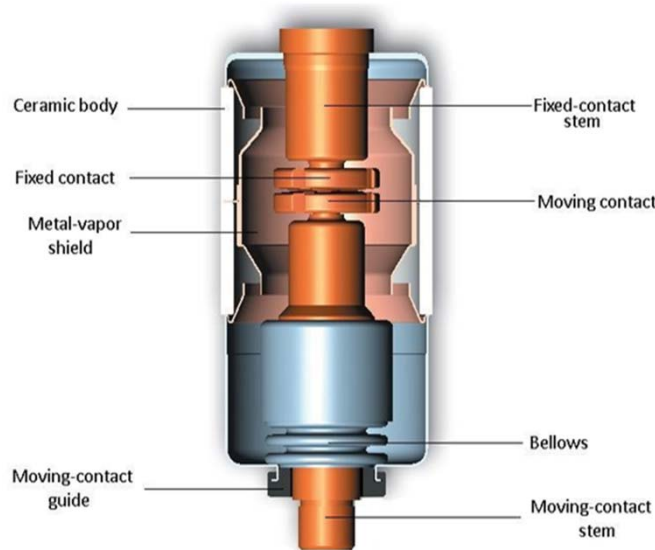
Figure 2: Internal View of a Vacuum Interrupter

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 lifespan/number of operations specs are up to 10 times those of the older technologies; furthermore, 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 a VIs is so long-lived is because of their simple, yet rugged construction.

Other advantages of VIs include the following:

- They are relatively compact and sealed.
- 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).
- They have the longest expected service life of any interrupting method.
- When VIs experience one of their relatively rare failures, the resulting damage is often much less than air-magnetic interrupters. However, they still can fail spectacularly, causing great damage.
- The low-mass movement allows for a lighter operating mechanism that is cheaper and lasts much longer.

VI Operating Principals

The VI's high interrupting capacity is based on:

$$V = \frac{apd}{In(pd) + b} (Eq1)$$

the 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 [4].)
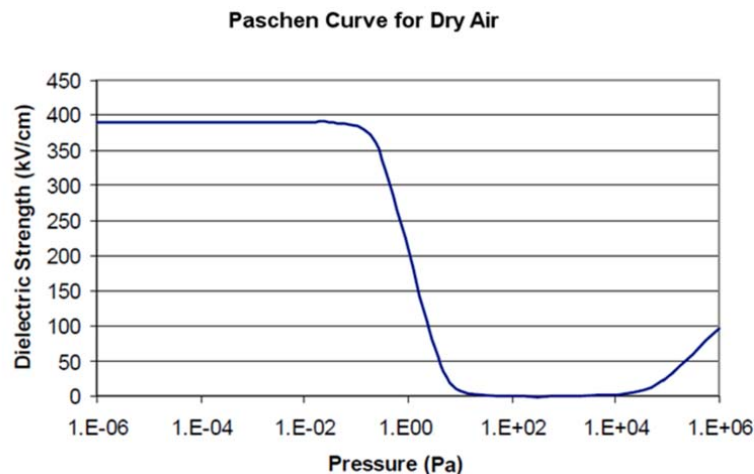

Figure 3: Paschen Curve for Dry Air

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).[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.

VI Construction
The following discussion refers to Figure 2 and 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.

Contact Mechanism
The contact structure comprises two parts – the moving contact assembly and the fixed contact assembly. The fixed contact is stationary and 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. [2]

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

- 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 maintain the vacuum level inside the VI.
- It also serves to keep the electrostatic field uniformly distributed both inside and outside the VI.
- 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), extremely low permeability to hydrogen (H2), 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, tight seals and low permeability are arguably the most important with respect to the long life of a VI. As discussed above, 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 related directly to the service life of the VI.
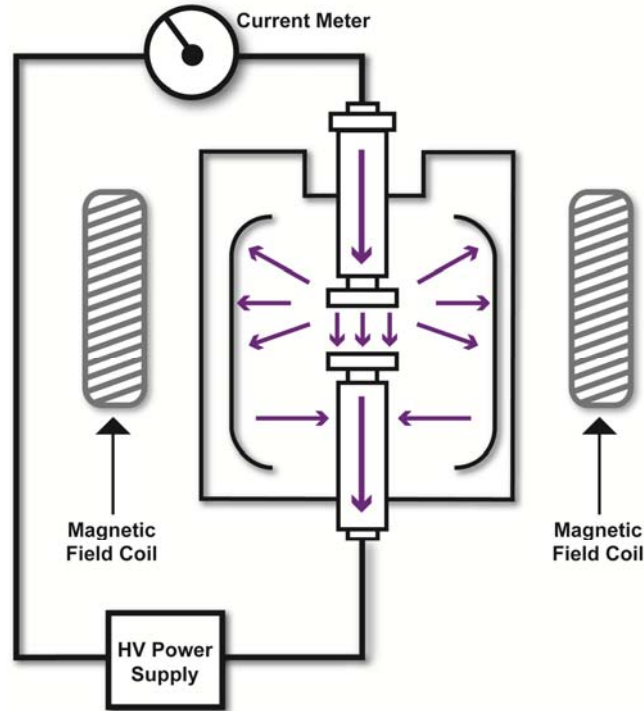
Figure 4: The Leak-Rate Test Set Up (Magnetron Atmospheric Condition (MAC) Test)

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 Test

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.

Leak-Rate Test (MAC Test)

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 (ion)

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. 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. A constant DC voltage, usually 10 kV, is applied to the open contacts, and the current flow through the VI is measured.[2]

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.

Although manufacturers' shipping criteria vary, most new VIs ship with internal pressures of 10^{-5} Pa or less.

The factory leak-rate test procedure is as follows:
- The internal pressure is determined as described in the preceding paragraphs.
- The VI is placed in storage for a period of time – usually a minimum of several weeks.
- 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.
- The difference between the two tests is used to develop a leak rate vs. time curve.

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.

VI Failure Modes
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 not an exception to this rule.

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

There are several possible types of VI failure.

- 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 the 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.
- Another common failure is internal arc flash-over 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.
- A third type of failure is 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 1 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.
- 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 shows an increasing number of high-pressure and dead-in-the-box, new VI in manufactured VCBs.

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

VI Field Tests
Of the three factory tests discussed earlier 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 determine the vacuum pressure inside the VI.

Contact-Resistance and High-Potential Field Tests
The high-potential test is a go/no-go result, and even 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 decrease in resistance 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's 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 20, 30, or more years. A huge percentage of them are well past their predicted life. Figure 5 shows a failed pole assembly. This failure occurred fairly recently. Industry studies are showing that an increasing number 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.

Predictive Vacuum Field Test

Based on the long-used factory leak test, a new field test is successfully being used to measure the vacuum pressure on service aged VI's.

Roadblocks and Solutions

The test equipment that is used to test vacuum in a VI is called a magnetron. In the past 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.
- 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.

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

Magnetrons for Field and Shop Use

With industry improvements in components and manufacturing capability, magnetrons such as the one shown at the right 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.
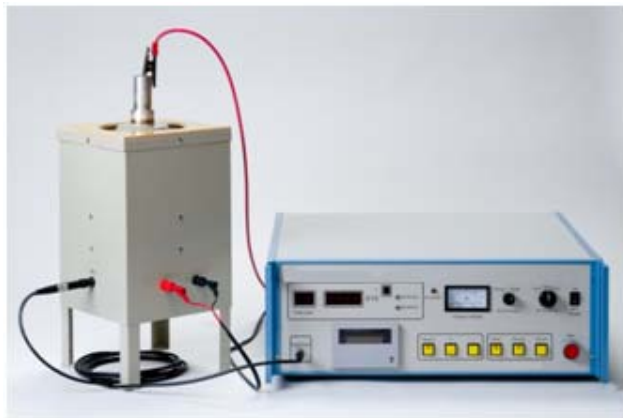

Figure 6: Portable Magnetron (right) with Test Stand (left)

Applying a 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. The device on the left side of Figure 6 is 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 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.

Since removing the VI from its breaker is time consuming and may lead to errors, flexible magnetic field coils (FMFC), such as that shown in Figure 7, have been developed.

Figure 7: Flexible Magnetic Field Coils

This specially designed coil is shown wrapped around the VI itself – a method not physically possible on all vacuum breakers. Placement of the FMFC cannot be arbitrary. Research has furnished the required information on where to place the coil to create reproducible, accurate results. Further research has shown that the FMFC can also be used around one or more field pole assemblies as shown in Figure 8.

Figure 8: FMFC Applied around Entire Pole

Promising research is ongoing into the possibility of other, more convenient types of magnetic field coils. It is believed that this research will lead to direct application field coils that will provide acceptable results.

Creating Pressure vs. Current Data

To determine the vacuum level in a VI, the relationship between the ionization current and pressure must be programmed into the test equipment. At present there are two well-researched and proven methods of developing this relationship. Both methods have been developed and tested using the laboratory setup shown in Figure 9.

Figure 9: Test Setup for Developing Vacuum Versus Current Flow Data

To create the vacuum vs. current curve, 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.

The data collected may be saved to create graphs, tables, or even equations that express the relationship.

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 are 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 field testing is performed. The tested pressure value along with other relevant data is entered into a modern CBM diagnostic and predictive algorithm. 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 previously 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 have proven to be equally accurate.

VI Size vs. Vacuum Level
Because of the large number of different manufacturers and models of VIs, developing individual curves for each vacuum interrupter will be a laborious task. Curves for a large number of the more common VIs are currently being developed, and curves for any VI can be developed on request.

Research shows 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 six or possibly seven generic curves that can be used successfully in determining the vacuum in most vacuum interrupters in service today.

VI Field Test Case Study

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.

In addition to the standard field tests, the vacuum level was determined using a current versus pressure table that was developed for the specific vacuum interrupters on the breakers. Evaluation criteria are shown in Table 1.

Table 1 VI Condition Based on MAC Test (Vacuum Pressure)				
Condition	Operations*	Contact Wear**	Pressure (Pascals)	Recommendation
A	< 1000	< 50%	$P < 10\text{-}5$	Retest in 10 years or less
B	< 1000	< 50%	$10\text{-}5 < P < 10\text{-}4$	Retest in 5 years or less
C	< 1000	< 50%	$10\text{-}4 < P < 10\text{-}3$	Possibility of failure place in non-critical service; retest annually
D	< 1000	< 50%	$10\text{-}3 < P\ 10\text{-}2$	High probability of failure; repair or replace
*If operations are > 1000 and breaker is used for motor sharing – degrade by one Condition (e.g. B to C)				
**(Actual Wear / Maximum Allowed Wear) * 100 where Maximum Wear = 0.125 in. (.32 mm)				

The criteria were applied as follows:
- The pressure criteria were used first to establish A, B, C, or D condition.
- If the contact wear was greater than 50% or if there were more than 1000 operations, the condition was elevated by one (A to B or C to D, for example).

Eight out of the 60 breakers were found to have a total of 10 vacuum interrupters that fell into Condition C and/or Condition D.

Two of the 10 interrupters had excessive contact wear and might have been flagged by the contact wear test alone; however, the other eight would not have been caught by the classic tests. If the MAC test had not been performed, eight vacuum breakers that were in imminent danger of failure would have been put back into service.

Since this was the first time that these breakers had been tested using the MAC test, there was no possibility of applying trending or prognostic programs. However, since leak rate is a trendable measurement, the MAC test will become extremely more valuable in the coming years.
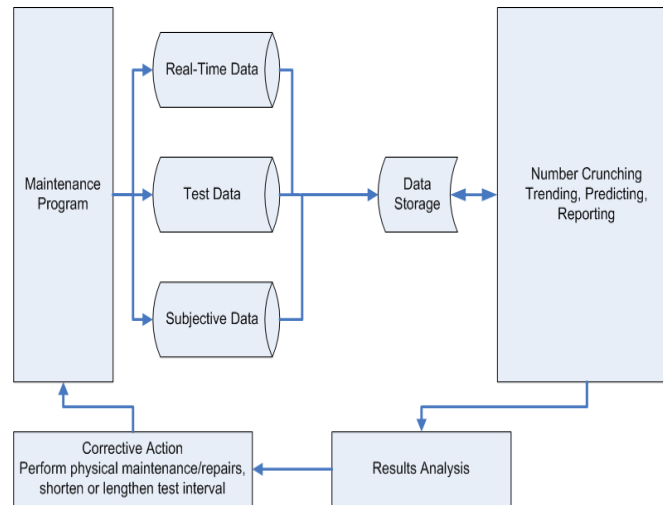

Figure 10: CBM Flow Chart

Condition Based Maintenance (CBM) Algorithms

For trendable test data (such as insulating oil screening and DGA tests), CBM mathematical algorithms have been developed and proven to:

- Provide predictions of future results out to two years with up to 95% accuracy and within ± one-half standard deviation.
- Allow much more accurate end-of-life predictions for large equipment.

Such algorithms go far beyond a simple linear trending approach by using multivariate self-learning mathematical structures and/or artificial neural networks.[3]

The CBM Process

Although a detailed description of the application of CBM algorithms is beyond the scope of this paper, Figure 10 is a flow chart of the process.

The following general steps explain the chart.

1. The maintenance and inspection program creates three basic types of data as follows:

    a. Real-time monitoring information
    b. Off-line test data
    c. Subjective data such as average temperature, age, and physical condition.[3]
2. The data is sorted and stored for both computation and archival purposes.
3. The CBM algorithm "crunches" the numbers.
4. The results are analyzed by the algorithm, and reports along with recommendations for further action are printed.
5. Corrective or replacement actions are then completed.

The Benefits of CBM

A CBM approach to maintenance provides three key rewards to those who employ it:

- Efficient scheduling of the frequency and intensity of maintenance
- More accurate asset life predictions allowing long-term operational and financial planning
- Improved employee and plant safety accruing as a result of the improved maintenance.

The payback is well-known by those organizations that employ CBM.

CBM and the MAC Test

Any statistical analysis package, such as a CBM process, requires a historical data set to work properly. Since MAC test is relatively new to field maintenance, the process is still early.

However, data is being collected, and the comparison of collected data to previous maintenance areas (such as the evaluation of insulating liquid) is very promising. In only a few years, we expect to see a marked improvement in maintenance efficiency and a reduction in the number of unexpected failures of vacuum interrupters.

Conclusions

As they reach the end of the 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.

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

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[3] In this case, the term subjective is used to indicate information that is not the result of an actual test.

Figure 11: The Maintenance Puzzle

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 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 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.

With the addition of the MAC test in the field, this need no longer be the case.

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 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.

Additional research is ongoing, and we expect to 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.

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Vita

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