MEDIUM-VOLTAGE VACUUM CIRCUIT BREAKER LIFE EXTENSION: AN APPROACH UTILIZING INDUSTRY STANDARDIZED MAINTENANCE INTERVALS, NEW TESTING TECHNIQUES, AND MODERN REPLACEMENT PARTS

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ABSTRACT

Vacuum circuit breakers are the dominant switchgear technology used in medium-voltage (1kV-38kV) power system applications due to their smaller size, increased service life, and ease of maintenance when compared to other alternatives. Throughout their service life, these circuit breakers must remain in optimum working condition – able to interrupt a fault quickly and reliably, even following long periods of inactivity during which the circuit breaker's mechanical and electrical components remain idle. With an ever-increasing percentage of medium-voltage vacuum circuit breakers in service nearing or already exceeding their design life, asset owners are facing difficult decisions about how to extend the usable life of their equipment beyond planned obsolescence; while at the same time maintaining the safety, reliability, and bottom line of their electrical systems. This paper will provide evidence which shows that simply using a breaker's age or number of operations to quantify mechanism health and schedule maintenance is ill advised due to the effects of outside variables which must also be taken into consideration. Additionally, it will describe how a three-tiered approach utilizing industry standardized maintenance intervals and philosophies during the life of the equipment, newly available testing techniques and technologies, and component upgrades with modern replacements can be applied to medium-voltage vacuum circuit breakers across the board in order to modernize the aging population and keep these valuable assets in service for many years to come.

INTRODUCTION

A properly structured life extension program for medium-voltage vacuum circuit breakers (MVVCBs) should seek to continually maintain and upgrade the equipment up to and beyond its planned design life to guarantee that it is operating at the highest levels of dependability; while also analyzing the economic impact of every maintenance decision and ensuring that safety is not being compromised. Life extension and modernization of MVVCBs and the electrical equipment they protect is a critical need for the aging power system infrastructure in the United States. As these circuit breakers age, they become more prone to failure – thus increasing the likelihood of an incident involving plant personnel and potentially costly damage to other equipment within the facility. When it comes to life extension of MVVCBs, a well-planned program can provide measurable economic benefits stemming from the added longevity and reliability of the equipment, while also providing less quantifiable, but very real, benefits resulting from improved safety.

Recommended intervals between maintenance can differ based on many variables, including original equipment manufacturer (OEM) guidelines, environmental and operating conditions, age and condition of the MVVCB, number of operations on key components, and the criticality of the circuit. Additionally, the prescribed interval will also be affected by the maintenance philosophy adopted by the equipment operator, facility management, and/or maintenance provider. Industry standards dictate how each of these criteria should be considered when dealing with service-aged MVVCBs to determine the ideal service intervals to maximize safety, reliability, and cost effectiveness.

In addition to recommended maintenance, MVVCBs must also be regularly tested to ensure proper operation during normal operating conditions, and accelerated testing must be performed on equipment subjected to extreme conditions such as high duty cycle applications or interrupting faults. Testing technology has vastly improved since the widespread adoption of vacuum circuit breakers (VCBs) in the 1970s, and many of the tests that were previously too cumbersome or time consuming to perform in the field have made their way out of the service shop and into the hands of field technicians. These tests were either not available or not accounted for when the OEMs were designing these VCBs to a specified service life. Now having the ability to perform these tests in the field quickly and with great accuracy has helped to increase the service life of MVVCBs.

Generally, VCBs will require more maintenance as they age, and new replacement parts from the OEM are not always available in a timely manner, at the right price, or at all. Downtime is very costly and access to high quality replacement components is essential to getting the equipment repaired quickly and back online. This need has spawned an entire market dedicated to providing replacement or aftermarket parts and assemblies that are often superior to the original components being replaced. Improvements can include use of modern materials, simpler designs with fewer components, or reduced maintenance requirements. For operators looking to maximize the life of their MVVCBs and bring them up to modern standards, this often means making continual upgrades throughout the lifetime of the equipment to ensure it is always up to date.

When properly maintained, MVVCBs can provide longer service lives than originally predicted by the OEM. By adhering to industry standardized maintenance intervals, staying educated about new test techniques and procedures, and incrementally replacing worn out or outdated parts, users can keep their equipment in good working condition to ensure that it will operate safely and reliably. This paper will present the main points for each of these strategies to help users keep their equipment in service well beyond planned obsolescence rather than replacing it at the end of its projected service life.

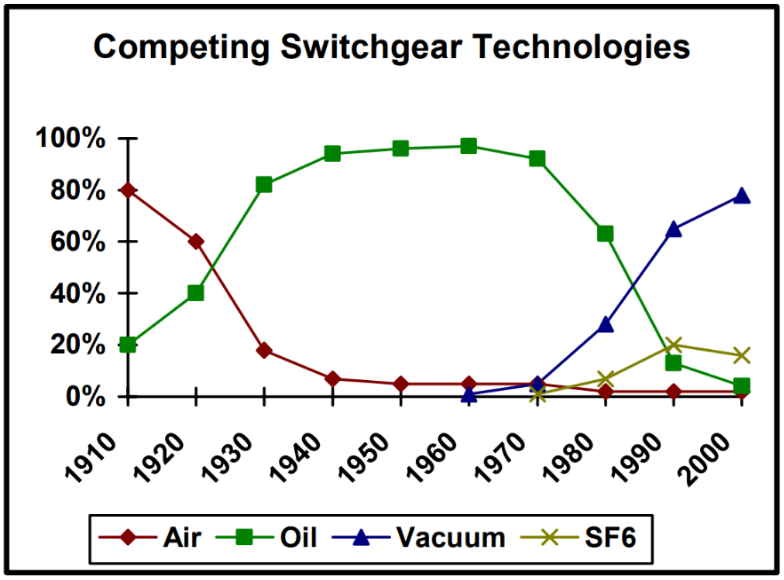
A BRIEF HISTORY OF VACUUM SWITCHGEAR

Switchgear performs a vital role in electric power distribution systems to rapidly clear faults or de-energize equipment on command. Switchgear can refer to any type of circuit breaker, disconnect switch, or fused element used to control, protect, or isolate electrical distribution equipment. Initially, simple knife switches provided an adequate means of interrupting circuits up to a few hundred amps, but as power levels and voltages rose into the range of today’s medium-voltage (MV) circuits (Those ranging from 1kV-38kV), these simple designs were not able to handle the increasingly higher fault currents. Needing a better solution, engineers turned to air and oil as the mediums for arc interruption that were first adopted by the power industry.

To interrupt a load, air circuit breakers (ACBs) separate contacts in air and extinguish the arc by utilizing a combination of characteristics from the arc, the air, and the magnetic field created in the arc chutes. The contacts degrade each time they are opened under load (More severely if they are required to interrupt a fault), establishing the need for continued maintenance to repair or replace them. As the requirement for interrupting ratings of ACBs increased, so too did the size of the breaker components needed to handle these larger loads – causing these breakers to become very large and cumbersome.

Although oil circuit breakers (OCBs) were also very large and cumbersome, they soon became the dominant MV interrupting medium primarily because of their ability to interrupt higher arc energies in a contained and safe manner. Unlike the open air contacts of ACBs, OCB contacts were completely submerged in oil which made them difficult to access for inspection and maintenance. In addition to these issues, increased regulation and stricter environmental requirements for the oil interrupting mediums made these circuit breakers less economical for most common applications.

Despite the drawbacks of both ACBs and OCBs, they remained best and only options for a long period of time. As shown in Figure 1 [1], air originally dominated the MV market until the 1920’s when oil replaced it to become the dominant interrupting medium. This remained the case until the 1970’s when VCBs were introduced and quickly overtook the majority of the market share. Despite a new technology, SF_6 gas, which came about in the 1980’s, vacuum continues to remain the dominant technology used in MV applications today.



Competing MV Switchgear Technologies during the 20th Century
Figure 1

Even though MVVCBs were not commercially available until the 1970's, research and development of the technology had been ongoing for decades. Vacuum switching technology was originally developed in the 1920's by a team at the California Institute of Technology who predicted the eventual commercial use in the power industry. Little research and development was done in the field during the 1930's and 1940's due to the economic depression, advancements in OCBs, and the war effort. But by the 1950's General Electric had resumed research and development of vacuum switches – drawing on technological advances in the support technologies required for their production, including vacuum systems, materials sciences, and clean assembly. During that same time, the first use of vacuum switch technology in electric power systems was developed using adaptations of existing communications vacuum switches manufactured by the Jennings Manufacturing Corporation. By the mid-1970's, many of the major OEMs, including General Electric, Allis-Chalmers, and Westinghouse, had introduced their own lines of MVVCBs. At this point the technology had taken hold and was well on its way to replacing OCBs as the dominant technology on the market. There has been continuous research and development devoted to the performance and application of vacuum interrupters (VIs) ever since.

STUDY OF AGING VACUUM CIRCUIT BREAKER MECHANISM PERFORMANCE

Previously, a study had been done that correlated the age of a VI to its internal pressure – showing that older VIs demonstrated higher internal pressures than newer VIs [2]. This paper was based on data collected during a large, all-inclusive study of as-found, service aged MVVCBs. For consistency among test subjects, all MVVCBs tested were the same make and model – though the sample size did include breakers with a range of ratings and VI types. In total, 815 VIs were individually tested and 246 mechanisms were analyzed. In an effort to validate the MVVCB life extension solutions presented in this paper, the information collected was reexamined to search for correlations between the age or number of operations versus mechanism timing data.

Importance of Collected Data

The referenced study focused on determining if any correlation exists between VI age, internal pressure, contact resistance, and AC HiPot leakage current. The results showed that there is a strong correlation between VI age and internal pressure, a minimal correlation between VI age and contact resistance, and no correlation between VI age and AC HiPot leakage current. That paper does a very good job in explaining the test methodologies and results, and as such will not be expanded upon here. Instead, what will be investigated for the scope of this paper is the MVVCB's operating mechanism first trip timing versus age and number of operations.

During the testing, alternating open and close operations were performed on each MVVCB three times and the timing was recorded for each phase individually. In the reevaluation of the data for this paper, the timing test results for the first open operation are being examined. This "first trip" data is important because, when a fault occurs, the MVVCB is expected to operate within its specified time-current characteristics. Unfortunately, this may not be the case due to environmental contaminants, hardened grease, vibration and other factors that can adversely affect the MVVCB mechanism's operating time. Because of these factors, it's not unusual for the operating time of a circuit breaker's first opening to exceed the OEM specified operating time. Additionally, the problem(s) which cause a circuit breaker to operate slowly are frequently cleared during the first operation of the breaker, meaning that the cause cannot be detected in subsequent testing. The act of operating the breaker will loosen hardened grease and exercise springs and other mechanisms so that when the breaker is tested again, the test will not represent a true "as-found" opening time.

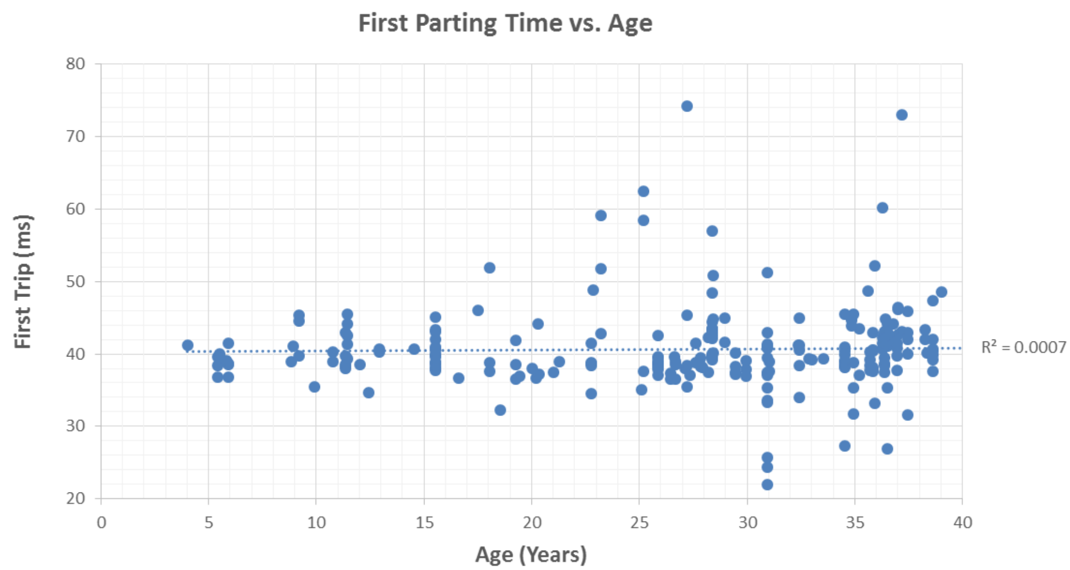
An arc flash analysis assumes that the over-current protective device (OCPD) will clear a fault within the OEM's specified time-current characteristics. The energy released during an arc flash is proportional to fault clearing time, so operating at rated speed is critical for calculations and protective schemes to be correct. A failed MVVCB, or even a slowly operating one, will result in higher incident energies – resulting in larger boundaries than specified or a higher level of PPE required than what is detailed on placards. Traditional maintenance testing of MVVCBs requires them to be opened and removed from the cell prior to conducting timing tests – therefore when a test is conducted it will not yield a true "first trip" operating time. First trip testing methods can provide a real-life operating time which can be compared to the assumed opening times used in an arc flash analysis. It's not unusual for the first trip time of a breaker with 5-10 years of inactivity to be greater than 100 milliseconds, and after the first trip it will typically fall within the safe limits of 30-50 milliseconds. If the first parting time of a MVVCB is greater than 60 milliseconds, it is not operating properly and must be pulled aside for further investigation and maintenance

Results of "First Trip" Time vs. Mechanism Age and Number of Operations

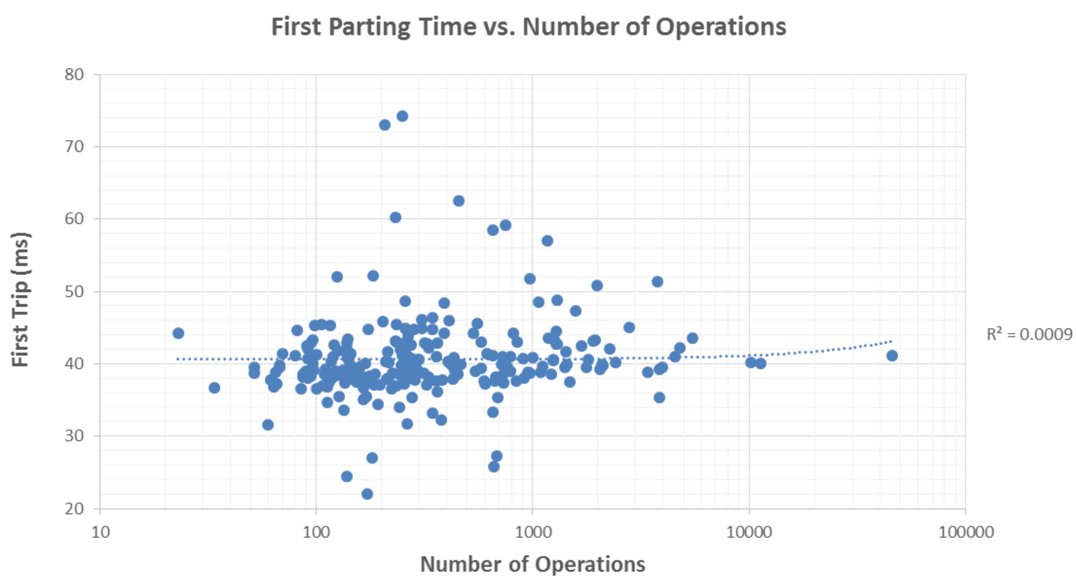
The data set was analyzed, yielding the results in Table 1 and Figure 2 and Figure **3**. Based on the data, it can be surmised that there is little to no correlation between the age or number of operations and the mechanism first trip timing as shown by the correlation coefficient (*r*) values of 0.0261 and 0.0298 respectively. These *r* values near zero signify a very weak relationship between the variables. Similarly, the r^2 value, which is the percentage of the y values whose variance can be explained by a change in x, is equally low.

Table 1
Correlation of "First Trip" Time vs. Mechanism Age and Number of Operations

Distribution	x Variable	y Variable	r	r^2
Linear	Age	First Trip Time	0.0261	0.07%
Linear	No. Operations	First Trip Time	0.0298	0.09%



Mechanism First Parting Time vs. Age
Figure 2



Mechanism First Parting Time vs. Number of Operations
Figure 3

Given the fact that no meaningful relationship exists, simply using mechanism age or number of operations alone is not enough to determine mechanism health and maintenance needs. While industry standards all point to a maximum allowable time or number of operations between maintenance, other factors must be taken into consideration as dictated by the maintenance philosophy set out within these same standards.

It is important to note that there are however variables which affect mechanism timing that cannot be accounted for in this data. First, there is no way to qualitatively or quantitatively include variations of ambient conditions while in service. It is likely, though not certain, that extremes in temperature and humidity will adversely affect mechanism timing. This is currently being investigated in a long term environmental study monitoring the ambient temperature and humidity of identical mechanisms for a future iteration of this research. Second, no data was available for individual mechanisms with respect to time since last operation or prior mechanism timing test results for comparison. Research has shown that inclusion of individual time-based data greatly improves the quality of the statistical analysis, so ten MVVCBs have been isolated from the present study to be fully reevaluated in a five year period. This will help to establish important mechanism timing information and provide a means for projecting future timing test results.

INDUSTRY STANDARDIZED MAINTENANCE INTERVALS & PHILOSOPHIES

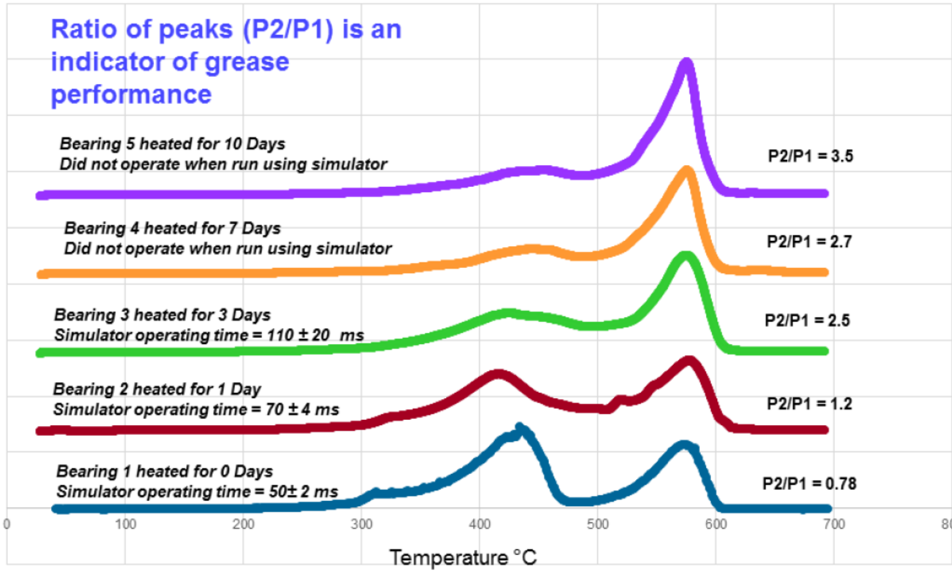
Many papers, articles, and standards have been written regarding the subject of recommended maintenance intervals for electrical equipment. While the scope of each of these documents varies and the content and recommendations may even contradict each other, there are conclusions that can be drawn from them as a whole. In regards to specific maintenance intervals for MVVCBs, all sources point to a maintenance interval not to exceed five years, due largely in part to the limits of lubrication life. Additionally these intervals could be reduced further if applicable conditions exists when applying the maintenance philosophy known as reliability centered maintenance (RCM). RCM is based on a combination of reactive, interval based, and condition based maintenance philosophies and has become the accepted industry standard. Finally, these industry standards set out requirements that must be followed, thus reinforcing the importance of calculating and adhering to the appropriate maintenance interval using procedures that have been carefully crafted to ensure safety and reliability are maximized.

The Limiting Factor: Circuit Breaker Lubrication Life

In a MVVCB, as with other circuit breaker technologies, there many different moving parts that require the use of lubricants, predominantly grease, to perform correctly. The lubricants used in these applications are carefully selected to maximize the service life of the parts and assemblies within the electrical equipment. There have been great advancements made in the field of lubricant development since these MVVCBs hit the market over 40 years ago and many studies performed over this time have provided valuable information about how these advancements can most beneficently be applied to aging electrical equipment. However, even with all this knowledge available, the majority of all circuit breaker operational failures below 38kV can be attributed to lubrication failure as a result of degradation due to age, temperature, contaminants, or combinations of incompatible lubricants [3]. Fortunately, these mechanical failures can be avoided with proper lubrication practices at properly scheduled maintenance intervals.

MVVCBs utilize many of the same components as products in other industries, but these complicated electromechanical devices are unique in that the application demands are quite different. Suitable lubricants for circuit breakers must be able to meet the distinctive requirements for these applications, including long periods of inactivity, large temperature variations, exposure to harsh environments, and lengthy time between services. Given these circumstances and knowing the vital role lubricants play in a MVVCB's electrical and mechanical operation, proper lubrication practices for these applications take on a very important role. It has been shown that effective lubrication can positively impact circuit breaker performance and extend maintenance interval periods [4]; and knowing the causes of lubricant degradation can help maintenance personnel develop practices to combat them.

As previously stated, grease is the predominant lubrication choice for various parts of a MVVCB mechanism due to its ability to stay in position once applied and seal the underlying material from corrosive or foreign contaminants. Grease is usually composed of 80-90% oil and 10-20% thickener, plus a small percentage of additives to aid in wear characteristics, corrosion prevention, oxidation resistance, or enhanced adhesion. The most unavoidable cause of grease degradation is age – as grease ages, the ratio of lubricant to thickener changes as shown in Figure 4 [4]. As the oil based lubricant portion of the grease evaporates over time, this leaves an abundance of thickener in the mixture. This evaporation causes the grease to change viscosity and stiffen, thus altering the properties of the lubricant. The thickener alone does not have the lubricating properties of the original mixture and will not act as needed when called on to do so.



Ratio of Lubricant to Thickener in Accelerated Grease Aging Test Samples
Figure 4

Temperature extremes can wreak havoc on a lubricant's ability to perform correctly as well. In addition to prolonged exposure to elevated temperatures, temperatures below the lubricant's specified lower limit can also have detrimental effects on the lubricant's properties. The higher the temperature to which the grease is exposed, the higher the rate of evaporation and oxidation, limiting service life. Grease is a poor conductor of heat and localized heating can result in grease oxidation – forming a film which can spread throughout the grease and completely coat parts with a varnish like substance. If the environment's ambient temperature is lower than the lower threshold of the lubricant's working temperature range, the lubricants may take on a non-viscous, almost gummy consistency and stiffen to a point which may actually prevent circuit breaker operation.

Grease or oil applied to parts within a circuit breaker will attract and capture dust, dirt, and other environmental contaminants. Over time, the concentration of these contaminants will increase and inhibit the lubricant's ability to do its job correctly, to a point that it may fall outside of the required specifications. Contamination comes in many forms, most notably dust, dirt, and moisture in the air; but the most damaging contaminants, including coal dust, cement dust, chemical vapors, or wood fibers, typically arise as a result of the operational environment of the equipment. Depending on their size and composition, contamination particles may even become trapped between moving parts and act as an abrasive – scoring metal parts and deteriorating seals until failure ultimately occurs.

The mixing of incompatible lubricants is another factor which contributes to their degradation. Lubricants are considered incompatible when the combination of two or more causes their collective properties to fall outside of their original specifications – examples of incompatible lubricants are shown in Figure 5 [5]. When combined, incompatible lubricants may experience chemical reactions that can decrease the performance capability and change their physical properties, resulting in lower heat resistance, changes in viscosity, or a decrease in shear stability. Unfortunately, many maintenance personnel are not aware of the potential issues caused by mixing lubricants, and thus may do more harm than good to the electrical equipment in the long run when reapplying lubricant. If a new type of lubricant must be introduced, the component should be disassembled and thoroughly cleaned to remove any trace of the previous lubricant prior to application.

	Aluminum Complex	Barium Complex	Calcium Complex	Lithium Stearate	Lithium 12-Hydroxy	Lithium Complex	Sodium	Clay	Polyurea
Aluminum Complex	–	I	I	I	I	B	I	I	I
Barium Complex	I	–	I	I	I	I	I	I	I
Calcium Complex	I	I	–	I	I	C	I	I	C
Lithium Stearate	I	I	I	–	C	C	I	I	I
Lithium 12-Hydroxy	I	I	I	C	–	C	I	I	I
Lithium Complex	B	I	C	C	C	–	B	I	I
Sodium	I	I	I	B	I	B	–	I	I
Clay	I	I	I	I	I	I	I	–	I
Polyurea	I	I	C	I	I	I	I	I	–

Grease Compatibility Chart
(Compatibility Rating: C – Compatible, I – Incompatible, B – Borderline)
Figure 5

Penetrating oils and sprays may be useful for certain applications, but it is not recommended to use them as a lubricant on circuit breakers because they can dissolve and flush out previously installed lubricants and accelerate equipment failure. When compared to grease, these sprays have a much lower viscosity – meaning they flow easily and will quickly leak from their applied locations due to heat, gravity, and motion – ultimately leaving parts dry and unlubricated. Furthermore, the penetrating oil which does remain on the parts evaporates at a much quicker rate than grease, leaving behind a viscous coating that actually inhibits mechanism operation. The use of spray penetrating oil is a short term, temporary solution that lasts only a few weeks at best – its use is detrimental to the long term health of a circuit breaker and leaves conditions worse than before it was applied.

Maintaining the lubrication within a circuit breaker to OEM specifications is a significant task and the demanding requirements of circuit breaker applications make the task even more difficult. In fact, it is estimated that one in every four breakers in service has some type of lubrication issue [6]. Degradation of the lubricant over time by any one of the failure modes can have serious consequences on the circuit breaker and impact personnel safety, equipment reliability, and maintenance costs. In order to minimize the negative effects of lubricant degradation, regularly scheduled maintenance, including monitoring the lubricant characteristics and properties, can produce meaningful data when scheduling maintenance intervals. While cleaning the mechanism and removing all traces of the old lubricant is not required at every maintenance cycle, once the lubricant has degraded to the point that affects the operation of the circuit breaker, application of new lubricant is required. Developing proper lubricating practices and appropriate maintenance intervals are essential for selecting and establishing a maintenance philosophy that coincides with the facility's long term objectives.

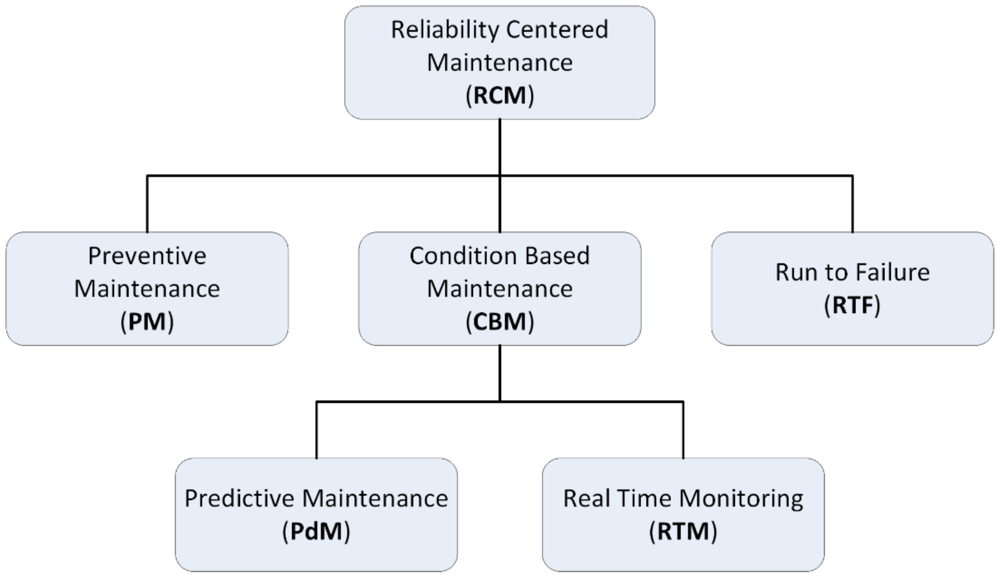
Maintenance Philosophy: Not A "One Size Fits All" Solution

The most basic maintenance strategy is a reactive, or run to failure (RTF), philosophy. Under this system, electrical equipment is deliberately allowed to operate until failure, at which point reactive maintenance is performed and the equipment is repaired or replaced. When discussing MVVCBs, this approach is not prudent due to personnel safety concerns and the potential impact failure would have on the greater electrical system. Yet, too often this policy is practiced in applications where its use endangers personnel and equipment. Only in rare circumstances can maintenance be suspended and the equipment allowed to run until failure before it is repaired or replaced – only when no consequences of failure exist in terms of safety, mission, environment, or security.

An interval based maintenance philosophy, more often referred to as preventive maintenance (PM), involves scheduled maintenance at preset intervals to ensure safety, reduce the likelihood of operational failures, and obtain as much useful life as possible out of the equipment before failure. This philosophy is based on the assumption that there is a fundamental cause and effect relationship between scheduled maintenance and operating reliability, and that the reliability of any equipment is directly related to operating age since all mechanical parts wear out eventually. Therefore, it should follow that the more often equipment is maintained, the better protected it is against the likelihood of failure. However, counterintuitively, studies have shown that many types of failures cannot be prevented no matter how comprehensive the maintenance activities performed are. Additionally, for many items the probability of failure does not increase with age and therefore a maintenance program which is based strictly on the age of the equipment will have little, if any, effect on the failure rate [7] [8].

Advances in monitoring and electrical equipment failure analysis have made it possible to identify the precursors of failure, quantify equipment condition, and schedule appropriate repairs with a higher degree of confidence than was previously possible when compared to performing strictly interval based maintenance. The availability of this data has emphasized the use of a philosophy known as condition based maintenance (CBM), which in turn has caused a reduction in reliance on strictly interval based philosophies. CBM is centered around monitoring equipment wear at measurable points of reference on vital components in real-time and predicting the probability of failure, while also taking into account certain outside influences which have an effect on the safety and reliability of the equipment. Once the probability of failure reaches an unacceptable level, repair or replacement is necessary.

Reliability centered maintenance (RCM) is a logical, structured framework for determining the optimum mix of reactive, interval based, and condition based maintenance practices needed to sustain the reliability of systems and equipment while ensuring their safe and economical operation. The concept of RCM was originally developed and proven in the aviation industry in the 1960's and has since been gradually adopted by the industrial sector. In the electrical equipment maintenance industry specifically, RCM continues to spread as the most prominent maintenance philosophy due to its endorsement in industry standards and its ability to utilize a combination of existing strategies that take into account all factors influencing maintenance intervals. As shown in Figure 6 [8], these principal maintenance strategies, rather than being applied independently, are integrated to take advantage of their respective strengths, thus maximizing facility and equipment reliability while minimizing costs.



Components of a Reliability Centered Maintenance (RCM) Program
Figure 6

Most MVVCB service manuals contain some type of information concerning usage or time-based intervals for PM; however, such “one size fits all” recommendations may not be applicable for certain applications due to environmental and operating conditions, the criticality of the circuit, and/or the condition of the equipment. Properly scheduled maintenance using an RCM methodology will reduce operating costs, increase production, and decrease unplanned outages. Implementation of RCM can be costly up front as a baseline must be developed, requiring breakers to be removed from service, tested, cleaned, inspected, lubricated, and reassembled.

While the entire scope of establishing and adhering to an RCM program is too extensive for this paper, readers may find more information in the most recent editions of applicable industry standards. These standards, including those maintained by NETA and NFPA, are helping steer the industry from outdated maintenance philosophies to RCM based philosophies and provide detailed information on how to apply RCM as well as reliability data for many types of electrical equipment.

Industry Standards: What the Experts Have To Say

There is no such thing as the perfect piece of electrical equipment – all types and styles, including MVVCBs, have design limitations that make them fallible. No matter which maintenance philosophy is applied to the equipment, it cannot improve upon the inherent reliability which is dictated by the equipment’s design. Rather than try to do the impossible, RCM acknowledges these design limitations and seeks to sustain the design level of reliability throughout the life of the equipment in an ongoing process. Industry standards are in place to help maximize equipment safety, value, and reliability by addressing failure characteristics and focusing on maintaining system function over individual component function while overcoming design life limitations to extend service life. While these industry standards are steering the shift towards RCM practices, it is important to note that they all still stipulate some maximum allowable maintenance interval when dealing with MVVCBs.

When it comes to the question of how often MVVCBs should be maintained and what maintenance should be performed, there are two main sources for answers: ANSI/NETA MTS, *Standard for Maintenance Testing Specifications for Electrical Power Distribution Equipment and Systems* and NFPA 70B, *Recommended Practice for Electrical Equipment Maintenance.* Both make recommendations about maintenance intervals and what specific maintenance is required for particular electrical devices [9]. The ANSI/NETA MTS touches little on maintenance philosophies and differing types of maintenance programs, but does acknowledge that the ideal program is reliability based. This standard does an excellent job of covering the electrical testing, maintenance requirements, and visual/mechanical inspections for virtually every piece of electrical equipment in an electrical power system. In response to requests for a maintenance interval timetable, ANSI/NETA has come up with the information found in Appendix B of the MTS, which outlines a matrix based multiplier approach to maintenance intervals for facilities which have not yet adopted RCM practices.

Table 2 [10] below shows the maintenance frequency matrix found in Appendix B of the MTS. The multiplier is derived from the table by choosing both the equipment's reliability requirement to the entire electrical system and the equipment's condition. For example, equipment that has a low reliability requirement and is in good condition would have a multiplier of 2.5. Using the data for MVVCBs found in Table 3 [10] as a reference, each of the recommended intervals is multiplied by 2.5 to come up with the maximum allowable interval, or 5 years based on the example for MVVCBs (2.5 x 24 months = 60 months, 60 months / 12 months/year = 5 years). In addition to the reliability requirement and equipment condition, application of the matrix when determining maintenance frequency should take into consideration the results of historical test data as well as other criteria such as OEM guidelines, environmental and operating conditions, age and number of operations, loading, how the circuit breaker is being used, etc.

Table 2
ANSI/NETA MTS-2011 Appendix B - Maintenance Frequency Matrix

MAINTENANCE FREQUENCY MATRIX				
		EQUIPMENT CONDITION		
		POOR	AVERAGE	GOOD
EQUIPMENT RELIABILITY REQUIREMENT	LOW	1.0	2.0	2.5
	MEDIUM	.5	1.0	1.5
	HIGH	.25	.50	.75

Table 3
ANSI/NETA MTS-2011 Appendix B - Frequency of Maintenance Tests (Partial)

Inspections and Tests Frequency in Months (Multiply These Values by the Factor in the Maintenance Frequency Matrix)				
Section	**Description**	**Visual**	**Visual & Mechanical**	**Visual, Mechanical, & Electrical**
7.6	Circuit Breakers			
7.6.3	Vacuum, Medium-voltage	1	12	24

The ANSI/NETA MTS differs from NFPA 70B, in that it doesn't cover anything beyond what tests to perform and what the results should be – it is a "what to do" specification, whereas NFPA 70B helps to bridge the gap on electrical maintenance requirements in a "how to do it" format. Table 4 [11] from Annex I of NFPA 70B provides an initial guideline for the maintenance intervals of MVVCBs which are recommended to have service performed annually and tested every three years. Similar to the ANSI/NETA MTS, this document also stresses that other factors such as environmental or operating conditions should also be considered and may dictate a different frequency of maintenance other than suggested in the annex. Additionally, NFPA 70B contains sections which deal specifically with the maintenance of equipment that dictates long intervals between shutdowns, and notes that that maintenance, inspection, and test methods are essentially the same regardless of whether the electrical equipment is shut down frequently or operates for long periods of time uninterrupted.

Table 4
NFPA 70B Annex I - Maintenance Interval Guidelines (Partial)

Item/Equipment	Task/Function	Interval	Reference
Vacuum Circuit Breaker	Visual Inspection / clean / adjust	Annually	8.4
	Contact checks / vacuum integrity	3 years	8.5.1, 8.5.2
	Electrical tests	3 years	20.9, 20.10.2.5

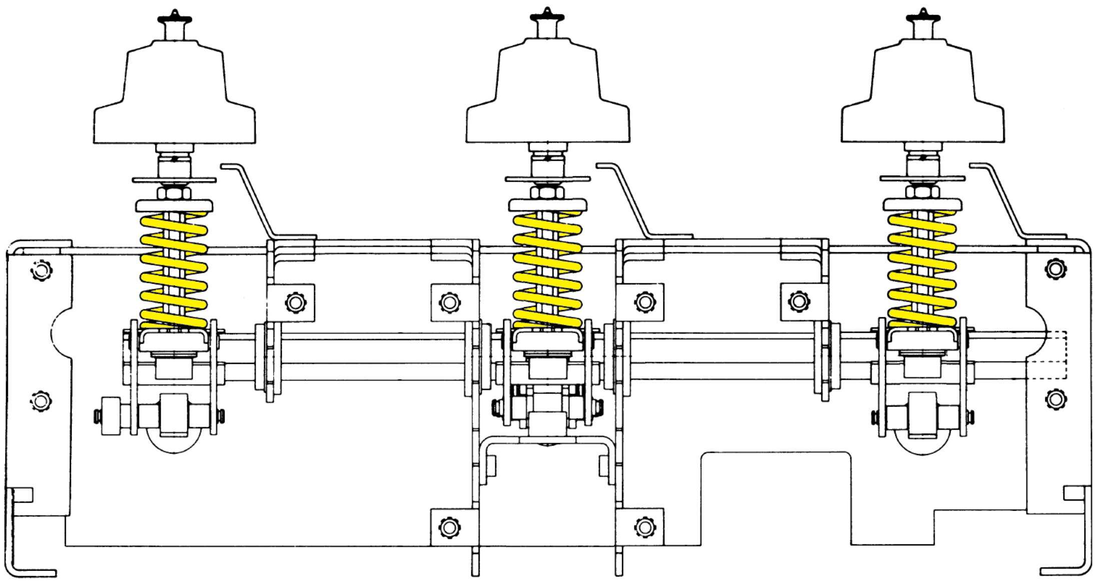
Electrical equipment deterioration is normal under all operating conditions and, left unchecked, can cause issues and eventually lead to equipment failure. The deterioration caused by factors such as a hostile environment, overload, or severe duty cycle has differing effects on different systems within a MVVCB, none of which are affected as badly as the circuit breaker's lubrication. An effective RCM program will identify these factors and provide measures for addressing them at the proper intervals to ensure that safety and reliability are maximized and cost is minimized. Even though industry standards are steering the shift to RCM practices, it is important to note that they all recognize the influence outside factors have in determining proper intervals while still stipulating a maximum allowable maintenance interval of no more than 5 years when discussing MVVCBs.

NEW TESTING TECHNIQUES

MVVCBs are some of the most important components in modern electric power systems and must always be capable of operating properly at any time. To protect sensitive and costly components downstream, these breakers must operate quickly and reliably when an issue is detected within the power system – often after months or even years of inactivity during which the breaker's mechanical and electrical components are never operated. Even though circuit breakers are reasonably reliable, failures do occur – potentially resulting in serious consequences in terms of both personnel injury and equipment damage. To minimize failures, MVVCBs must be routinely tested and maintained to ensure proper function when called to action. New developments in reliable, efficient test instruments and testing methods have made it possible to improve and re-evaluate historical methodologies.

Wipe Spring Force: What is it and Why is it Important?

On a MVVCB, wipe is the additional over travel of the mechanism past closing the butt contacts inside the VI. The energy stored in the closing springs of the circuit breaker mechanism provides a set amount of motion, and during a closing operation the first portion of this motion is used to rapidly close the VI contacts. The remaining mechanism travel, known as wipe, is used to compress a preloaded spring, shown in yellow in Figure 7 to apply and maintain a constant force on the VI contacts while the breaker is closed.



Wipe Spring Placement on a Medium-Voltage Vacuum Circuit Breaker
Figure 7

Wipe has three main purposes: to provide a means to compensate for contact erosion over time, to provide a force which forms the contacts to one another to maintain a low contact resistance, and to counteract the “popping”, or “blow-off” force caused when a large amount of current travels through the contacts. As the contacts inside the VI erode over time, the additional stroke in the mechanism ensures that the contacts are able to fully close, which in turn decreases amount of wipe. This contact erosion stems from surface degradation during high current arcing and causes high resistance across the contact surface, limiting the current that can be passed through them. But, by applying a large force on the contacts during a closing operation, the contacts form to one another and the resistance can be minimized to allowable values. Lastly, high current conditions, such as during faults, create an electromagnetic force, known as popping force, which attempts to spread apart the VI contacts.

The majority of technicians and service shops are aware of the effects of a poor wipe setup on the breaker due to contact erosion and resistance, as well as which instruments and procedures can be used to test for them. However, many are unfamiliar with arguably the most important purpose of wipe – counteracting the electromagnetic popping force that attempts to separate the contacts during faults. The actual contact area between the fixed and moving butt contacts in a VI is a small fraction of the total apparent area of the contacts due to disparities on the surfaces [12]. As current flows through the limited number of points on the contacts, it is constricted and the magnetic field created by the converging and diverging current in opposite contacts tends to force them apart. The strength of the magnetic field responsible for this force is proportional to the current passing through the contacts, and as the current approaches the threshold to separate the contacts they may begin to experience melting at the contact points.

Testing standards require VCBs to withstand full fault current for up to three seconds while the VIs remain closed. Therefore, it is critical that the force acting upon the closed contacts exceed the electromagnetic popping force so that the contacts remain closed during high current faults that the breakers must withstand. If the force is not sufficient to hold the contacts closed, the contact area will decrease as they begin to separate, leading to high resistance and formation of a metal vapor bridge between the contacts. This arc melts regions of the contacts and its effects add to the opening force, separating the contacts further.

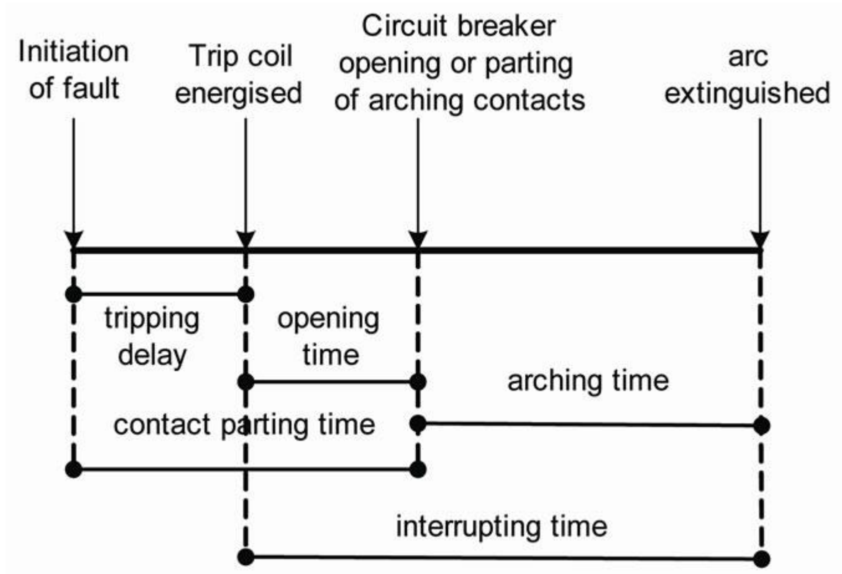
Inadequate wipe adjustment or spring force can lead to premature failure of the VIs and MVVCB. However, too much spring force on the contacts can cause problems as well. Improper adjustment resulting in excessive wipe spring force on the VI can cause cracks in the contact faces, excessive bellows wear, and even bent poles. Proper mechanism adjustment within the wear limits of the VI will ensure enough force on the contacts to maintain low contact resistance and counteract the electromagnetic popping force during faults. Contact resistance and wear can be checked periodically or when a VI is replaced, but the wipe spring force acting on the VI is a different story. Wipe springs are generally very stout and even a small change in the wipe spring adjustment can have a large effect on the force on the contacts.

Wipe Spring Spring Rate Test Setup
Figure 8

The wipe force acting on a VI is a critical design specification that does not receive enough attention during routine maintenance, repair, or the remanufacturing process. In order to get the poles of a breaker in sync technicians will often make adjustments to the wipe spring without regard to the effect these maladjustments may have on the VI's ability to withstand a fault. Additionally, MVVCBs which have been subjected to high temperatures for prolonged periods of time or high duty cycles should have each spring within their mechanisms removed and checked, similar to the test setup shown in Figure 8, to ensure the spring rate is within OEM specifications and capable of supplying the required force. Without this data, a VCB should not be allowed in service.

Parting Time vs. Clearing Time: Effects on Arc Flash Calculations and How to Measure in the Field

MVVCBs, as well as other electrical distribution switchgear, all have an interrupting rating which is defined as the RMS value of symmetrical current that the circuit breaker can interrupt without being destroyed or causing an electric arc with unacceptable duration. It is impossible for a circuit breaker to instantaneously interrupt a circuit at the exact start of a fault – instead, an (OCPD) utilizes a time-current curve in a band bound by minimum and maximum values of total clearing time, indicating how long it will take to clear a fault for a given magnitude of current. The rated clearing time of a circuit breaker is the maximum allowable length of time between energizing the trip circuit and the interruption of the main circuit in all poles and is figured as the sum of the circuit breaker's sensing time, unlatching time, and arcing time as demonstrated in Figure 9 [13].



Phases of Total Clearing Time in a Medium-voltage Vacuum Circuit Breaker
Figure 9

While many variables are considered when performing incident energy calculations for an arc flash hazard analysis, arguably the most important variable is the arcing time which defines the duration of the arc flash. Using the equations provided either by IEEE 1584 or NFPA 70E, the incident energy value is calculated in cal/cm^2 at a specific working distance and used to select appropriate protective equipment and clothing for each piece of electrical equipment analyzed. The arcing time used in these equations is typically chosen as the total clearing time of the protective device located upstream from the equipment being analyzed. Newer MVVCBs will clear a fault in three to five cycles, but if the total clearing time value used in the incident energy calculations changes or is inaccurate, then the results of the arc flash study will no longer be correct and personnel may be in danger.

The total clearing times used in incident energy calculations are based on what the protective devices are supposed to do. If a breaker's interrupting time is rated at five cycles, as most are, how can it be proven that the OCPD will perform as advertised? Short of removing each breaker from service and testing it at a laboratory, performing a timing test is the best option if the breaker can only be out of service for a limited amount of time. Parting time gives a clear metric for the mechanical reaction to a trip command and generally has a relationship to the total clearing time. The time correlates with the MVVCB's operating mechanism health and lubrication state.

Until recently, circuit breaker time travel analysis was a difficult and cumbersome test to perform in the field. Users had to utilize a separate power supply and have knowledge of the circuit breaker's internal wiring to operate the breaker outside of the cubicle. But with the introduction of modern, easy to use timers that incorporate the timer and power supply into one unit, users can now perform this test quickly and easily. Additionally, compatible secondary disconnect plugs are available to ensure users connect the device correctly to prevent damage to the breaker and/or tester. Setup and operation of these test instruments only takes a few minutes when properly prepared. Even if operational constraints will not allow the breaker to be removed, a vibration analysis will offer at least a chance to determine the overall mechanical condition and timing to ensure the equipment performs in accordance to the values used for the arc flash study. This has to be done during an actual switching event, but the data can be extracted while the MVVCB is still fully installed.

Maintenance and testing must be performed routinely in order to minimize the risk of having an unintentional time delay in the operation of the MVVCB. If proper maintenance and testing are not performed, extended clearing times could occur and the time delay will adversely affect the results of flash hazard analyses. As electrical power systems evolve to meet growing demand, shorter breaker clearing times will be required to address higher fault currents and minimize damage due to breaker failures. A number of factors affect overall breaker fault clearing time, but the most impactful is the operating time of the circuit breaker, which includes the operating time of the primary protective relays. But if a circuit breaker timer only gives parting time, what is really known about the total clearing time and what has to be assumed? Technicians must be aware of the limitations of the tests they are performing and how to properly read the results, otherwise the data may be misinterpreted, potentially endangering service personnel.

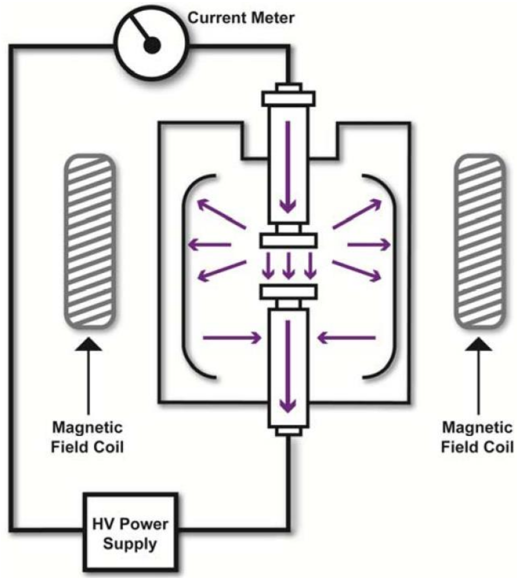
Vacuum Interrupters: Predicting Their Remaining Life in the Field

A means of circuit protection is necessary in order to safeguard service personnel, electrical equipment, and productivity against the effects of shorts, faults, and dangerous arcing conditions. For MV applications, the means of circuit protection has, in the last half century, been dominated by VCBs. The preference of vacuum over other alternatives such as air, oil, or SF_6 gas is due to vacuum's ability to interrupt high energy faults quicker than the alternatives – improving personnel safety and equipment reliability. The VIs at the heart of these circuit breakers are the result of almost a century's worth of research and development and are marvels of modern engineering and manufacturing. But, for all the time spent perfecting their design, VIs are still susceptible to failure due to contact erosion, loss of insulating ability, and loss of vacuum due to damage or age.

When VIs are manufactured there are three tests used to validate their function prior to being released from the factory: contact resistance, high potential withstand, and leak rate. Of these tests conducted at the factory, only two seen widespread use in the field – the contact resistance test and the high potential withstand test – neither of which is able to determine the level of vacuum pressure inside the VI. By its nature, the VI is hermetically shielded from the outside world, making it difficult to quantify the state of the internal components during routine maintenance. Only leak rate testing provides results beyond "pass/fail' that can provide quantifiable data about the integrity of the VI's vacuum pressure. If maintenance technicians possessed this data about the internal pressure of the VI, it would allow them to use RCM procedures and programs that would result in higher equipment uptime, longer lifecycles, and ultimately lower operating costs.

Until very recently, leak rate testing has not been feasible for field applications due to the size, cost, and complexity of the equipment necessary to generate the magnetic fields required. However, recent research and development and technological advances have enabled manufacturers to build robust and reliable portable leak rate test equipment with these capabilities. This has major implications for testing outside of the factory, as technicians can now perform leak rate tests in the field, thus generating quantifiable data that can be used as part of an RCM program.

Leak rate testing is based on the Penning Discharge Principle which states 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 ion current flow between the plates is a function of the gas pressure, the applied voltage, and the magnetic field strength. Figure 10 [14] shows the basic test setup for a VI leak rate test. For field testing, the VI is placed in a portable fixed magnetic coil or a flexible cable is wrapped around the test specimen a prescribed number of times. When the test is started, high voltage DC is applied to the VI and the baseline leakage current is measured. Next, a DC voltage pulse is applied to the magnetic field coil during a second application of the high voltage DC and the total current is measured during the pulse. The ion current is calculated as the total current minus the leakage current. Since the magnetic field and the applied voltage 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.

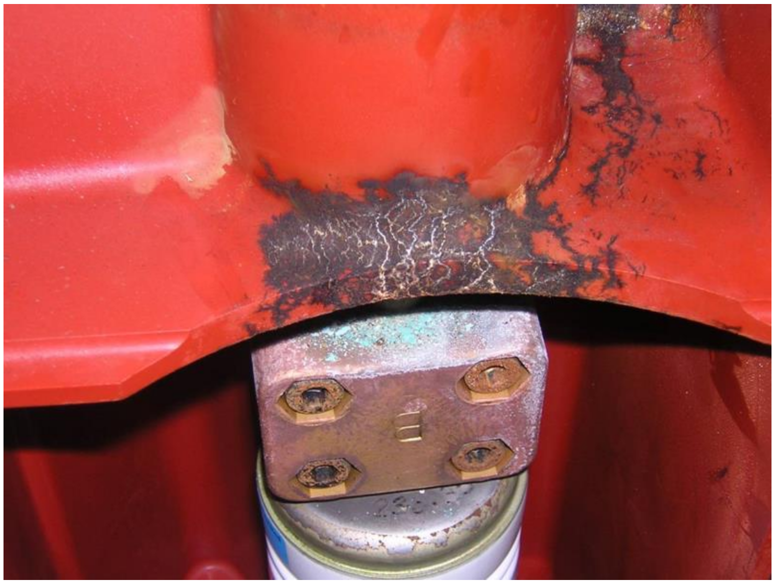


Vacuum Interrupter Leak Rate Test Set Up
Figure 10

As previously noted, the pressure inside a VI will increase with time. There will always be some leakage in even the best VIs, and 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 leak rate can greatly shorten VI life. When VIs within circuit breakers are tested during routine maintenance using traditional methods they go back into service with only the guarantee that it will function at the moment, with no forecast about future results. Setting up for and performing the leak rate test is no more difficult than many of the field tests that maintenance personnel are already familiar with and the results are extremely accurate in determining the pressure inside the VI. An RCM program requires data gathered during testing to work efficiently and yield the best results. With continued adoption of leak rate testing, the electrical industry can expect to see a marked improvement in maintenance efficiency and a reduction in the number of unexpected failures of VIs.

Continuous Partial Discharge Monitoring: What's the Buzz About?

Partial discharge (PD) is a localized dielectric breakdown within insulators due to voids, cracks, air bubbles, or foreign inclusions and appears when the irregularity leads to a non-uniform electrical field in systems running under high voltage stresses. Irregularities may include internal issues caused by manufacturing processes and/or external issues due to installation, handling, aging, or environmental contamination. In addition to these factors, PD is also affected by outside influences such as system voltage, load, temperature, humidity, vibration, and atmospheric pressure. Some PD events are invisible to the naked eye and can be difficult to detect and monitor, while some manifestations will occur as corona discharges which are usually visible via a steady glow, or as arcing. When left unmonitored, PD events can become very dangerous and, once started, will not cease without corrective actions. PD events do not immediately result in breakdown of the insulation, but the consequences of continuous PD in an insulator result in energy loss due to heat, sound and light. Over time these effects will damage the insulation's integrity, as shown in Figure 11, beginning at a small point and eventually propagating to a breakdown of the insulation and complete failure of the system.



Effects of Unmitigated Partial Discharge in Insulation
Figure 11

Early MV electrical equipment was constructed using organic insulation that would eventually fail as it absorbed moisture over time, and the use of heaters in the switchgear, while helpful, only delayed the inevitable. As advances were made, the industry slowly moved to porcelain based insulation technology in MV applications. About the time that VCBs were introduced, advanced plastics, fiber based insulation, and epoxy were being also being introduced with these offerings. Today, current MVVCBs have much better insulating systems, but if they are not maintained, kept clean, and well heated, catastrophic failure is still a possibility. The expected life of MV insulating system components is generally considered greater than 20 years, and modern insulation materials will far exceed this if kept clean and dry.

Many possibilities to detect and measure PD are available on the market and are relatively widely used; however the application of each is very site specific as the switchgear environment and age of the equipment all dictate which method is applied. A major disadvantage of most of these techniques is that they are only performed periodically rather than continuously. Periodic methods not only require the use of valuable resources but will also only provide a snapshot of the insulating system's current health. Additionally, many parameters influence PD and, depending when the readings are taken, these may give a completely inaccurate picture at that point of time. Permanently installed systems intended to detect long-term degradation of the switchgear insulation system use advanced diagnostics designed to look for PD events during operation and monitor the data trends to determine the severity and location of PD signatures.

One way to continuously monitor switchgear assets is by utilizing electromagnetic field detection, which picks up the radio waves generated by PD events in insulation. This newly adapted technology is ideally suited to applications which require a non-invasive, real-time, wireless, continual monitoring solution for the most demanding applications such as where switchgear access is limited or maintenance can be difficult and dangerous. Using installed antennas within the switchgear, data acquisition instruments scan multiple frequencies within a frequency range, thus avoiding disturbances of other transmitters on a single frequency. Every scan consists of thousands of observation cycles and a real-time algorithm analyzes the received signal patterns to monitor for PD signatures within each cycle. These systems may be connected to existing SCADA or local alarm systems to provide real-time feedback about PD which is necessary for an RCM program. These radio frequency systems are able to accurately correlate the actual health of insulation system in terms of PD. Additionally, the antenna and data acquisition instruments can also be used for interrogating surface acoustic wave (SAW) based wireless, passive temperature sensors to provide a valuable add on to the monitoring system.

PD is a well-known risk in MV switchgear as well as all other high voltage assets and random failures due to insulation breakdown often occur between planned maintenance outages. As insulation systems age, they can become more susceptible to breakdown and continual monitoring for PD signatures can predict failure, thus avoiding damage associated with these failures. By only monitoring PD periodically, critical data can be missed or misinterpreted. Therefore, a continuous monitoring solution is the best way to observe PD in real-time to help prevent damage and downtime due to insulation breakdown related failures.

Testing is a topic that can be, and has been, discussed for hundreds and hundreds of pages. That level of detail is beyond the scope of this paper, and for the sake of brevity, it will be narrowed down to the focus only on the ANSI/NETA MTS – any reasonable attempt by maintenance personnel to meet this standard will put them well ahead of the rest of the world. According to the ANSI/NETA MTS, the following tests should be done when performing maintenance on a MVVCB: Visual inspection, mechanical tests, electrical tests, and mechanical/electrical test value comparison and analysis. Some of these tests were not available, nor were they accounted for, when the OEMs were designing these breakers to a specific service life. As technology and understanding have improved, many of the tests which were previously only able to be performed in a service shop have made their way to the hands of field technicians. Having the ability to perform these tests quickly and with great accuracy in the field has helped to increase the service life of the breakers these tests are being performed on.

MODERN REPLACEMENT PARTS

In addition to regularly scheduled routine maintenance, MVVCBs may also require component upgrades throughout their life cycle to extend their service life. When faced with the choice of continued support of legacy equipment or replacing it altogether, the costs of total replacement often outweigh the benefits – facility managers must take into account the initial capital cost, along with potential disruption to the facility's processes and workflow during the course of swapping out equipment. The cost of lost production can be substantial unless circuits can be rerouted temporarily during the removal of old equipment and installation of the new equipment. The more cost effective and environmentally friendly alternative is usually to leave the switchgear housing in place and upgrade all or parts of the existing VCBs and controls with the latest state of the art replacement components as dictated by the facility's maintenance program.

Recent advances have given rise to a market of circuit breaker replacement parts and upgrades that can increase reliability, decrease maintenance costs, and even improve the switchgear's ratings. Any discussion of life extension requires an understanding that there is an entire industry beyond the OEMs dedicated to providing support for all types of circuit breakers. Every single part for all of the most common types of MVVCBs is now available either direct from the OEM or through other suppliers, and these non-OEM vendors will have the necessary parts available for the foreseeable future to continue to support legacy platforms. Problems within switchgear are often identified by maintenance personnel and diagnosing the cause to find the correct solution can be difficult. Often, these solutions require an in depth knowledge of electrical engineering, testing, and specialized equipment and may require a custom engineered approach in addition to equipment repair, upgrades, or replacements. With current advancements in technology and widespread availability of quality parts and services, older circuit breaker designs can be kept in service sustainably beyond their designed service life.

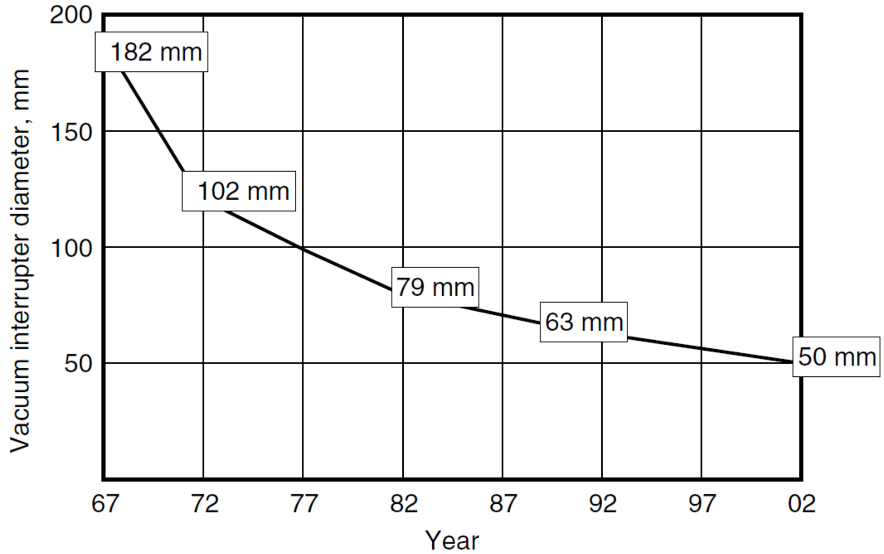
Today's Vacuum Interrupters: Higher Ratings and Better Reliability in Smaller Packages

When MVVCBs were introduced 40 plus years ago, VI failures were a rare occurrence. Since their widespread adoption over the ensuing time period, the aging fleet of VCBs in service today is experiencing more and more VI failures due both their number and age. In fact, VI failures are now an everyday occurrence with estimates of a failure every few hours in the United States alone. The wholesale offshore transfer of VI research and development and manufacturing has created a very real weakness in the ability to maintain these key assets which are used in every major power system in the United States. Even so, new technologies and advances in material science, arc control, construction, and assembly have had noticeable effects in terms of increasing the reliability and ratings while decreasing the size and costs of VIs over the last half century.

Current Vacuum Interrupter with Improved Ratings vs. OEM Vacuum Interrupter
Figure 12

One of the most significant improvements in VIs since their first usage in VCBs has been the use of state of the art contact materials. In a VI, the contact material determines the properties of not only the arc, but other important properties such as current chop and its tendency to weld. The development and application of advanced copper chrome alloys over other materials has been so successful that they are now almost universally used in VIs worldwide.

Another advancement modern VIs have over their older counterparts is the implementation of state of the art arc control contact geometry. Most VIs are able to evenly spread the arc over the entire contact surface during low current interruptions, but there are difficulties associated with interrupting high current that engineers had to address. When interrupting high currents the arc is constricted to a few spots on the contact surfaces, concentrating all of the arc energy over a small area which results in localized overheating, contact melting, and failure to interrupt. To solve this issue, engineers developed contacts which caused the self-induced magnetic field generated by the arc to help distribute the current more evenly to aid in extinguishing the arc. These novel designs utilized a radial magnetic field (RMF) to perform this task, and more recently the technology evolved to feature an axial magnetic field (AMF) to do so more efficiently. Better arc control geometries allowed the contacts to become smaller over time as shown in Figure 13 [15], which in turn has had the effect to reduce the size and cost of VIs.



15kV, 12.5kA Vacuum Interrupter Size Reduction over a 40 Year Timespan
Figure 13

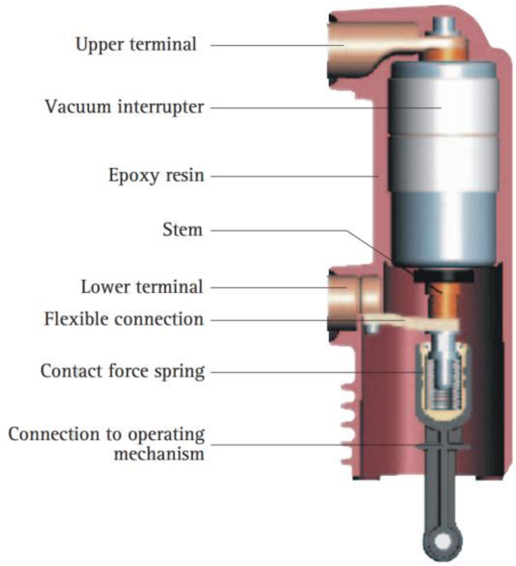
Since the contact size was continually being decreased, the design and manufacturing methods of the VI needed to change as well to take full advantage of the space saving advancements. Older VIs were complicated collections of parts which required dozens of individual components to be put together in subassemblies prior to final assembly. The pinch tube sealing method has now been replaced by a one “one shot seal off” operation within a vacuum furnace to seal off and join the components. However, design options were still limited due to the need for a “floating” shield to prevent metal vapor produced during arcing from building up on the inside of the two ceramic insulators and lead to breakdown. This necessity added complexity and cost to the VIs and resulted in the development of a shieldless VI which utilized only one ceramic insulator with no metal vapor shield. While this design is not used across the board for all VIs, research and design is ongoing with efforts to further implement it. This design drastically reduced the number of required components needed to assemble a VI, also simplifying the assembly process. These new manufacturing and assembly techniques allow the shelf live for newly designed VIs to greatly exceed the older designed counterparts.

Some VCBs were designed with ease of VI replacement in mind, while others were designed to replace an entire pole, and still others were designed to discard and replace the entire breaker. Suppliers have recently started to address the necessary components and methods needed to replace aging VIs which may no longer be available from the OEM. As a result of the current state of VI technology, VI replacements likely come with upgraded interruption and voltage ratings due to improvements in the ceramic insulating envelopes, contact materials, and manufacturing techniques. VIs can perform well in all MV switching applications required in modern power systems with exceptionally long life and low maintenance, but when failure occurs make sure to choose a modern VI to gain the benefits of almost a century’s worth of research and development.

Embedded Poles: The Next Step in the Evolution of the Vacuum Interrupter

Embedded VI poles were first introduced to the power industry in the 1990’s and established a new trend in MVVCB applications. The purpose of these products was to simplify the VCB’s pole assemblies by enclosing the VIs in a silicone or epoxy resin insulating material using specialized molding processes. Embedded poles have several advantages over standard VI pole assemblies, including their high dielectric strength in air, their suitability for use in a wide range of environmental conditions, their increased structural rigidity, and their ability to seal and protect the VI from dust, moisture, and impact. Due to research and development into this technology since their introduction, embedded poles are now established on the market and available for indoor and outdoor MVVCB applications, and because of their minimal maintenance requirements and compact and robust designs, these embedded poles offer a promising solution for legacy VI pole assembly upgrades.

A VI's internal dielectric strength from the contact gap within the sealed vacuum atmosphere is greater than its external dielectric strength which is limited by the insulation properties of air and is subject to environmental conditions such as condensation or contaminant buildup. But, the dielectric strength can be improved by embedding the VI in a solid silicone or epoxy resin as shown in Figure 14 [16] since the VI is protected from external contaminants and has an increased creepage distance. Recently, new epoxy formulations have been developed specifically for outdoor applications and boast many upgraded qualities including lower moisture absorption rates, UV resistance, improved thermal conductivity, higher impact strength, and lower temperature limits down to -75°F. In fact, this solution has been widely adopted for use in new IEC rated MVVCBs and has been approved in ANSI rated MVVCBs as well.



Embedded Pole Construction
Figure 14

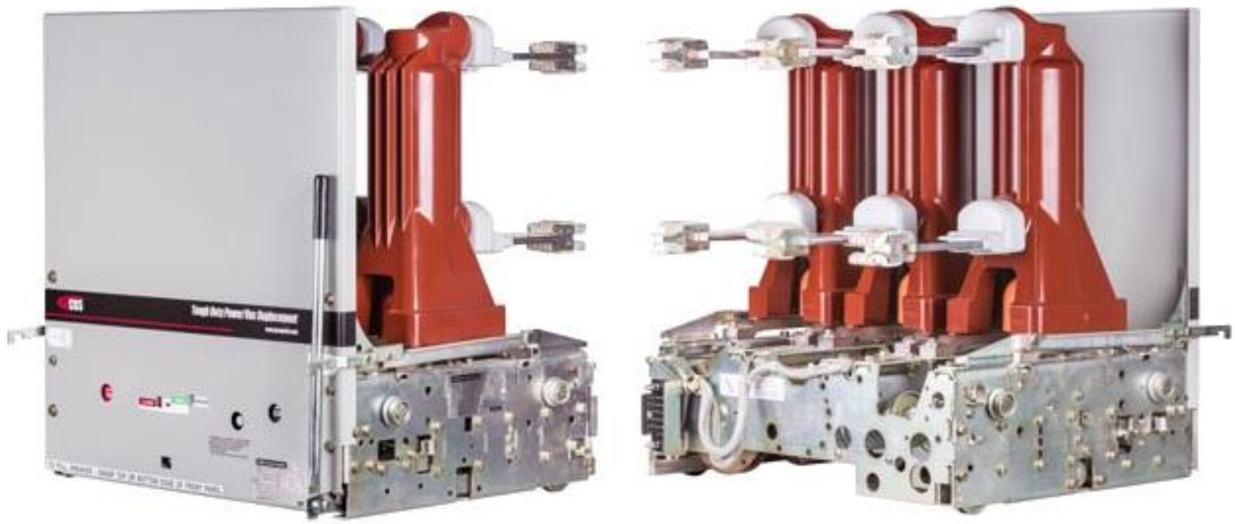
MVVCB parts suppliers have recently been working to develop embedded pole replacements for legacy circuit breaker pole assemblies as similar to those shown in Figure 15. These replacement embedded pole assemblies must be ANSI/IEEE C37 tested and certified for use on compatible circuit breakers to upgrade and extend the life of original equipment. If combined with proper mechanical maintenance of the breaker, these hardened and superior assemblies will enable the user to extend the life of the equipment another twenty plus years. The use of new encapsulated pole assemblies to upgrade older VCBs to this modern technology is available now in selected ratings and others will be available in the near future. The cost is very close to that of a VI replacement with core exchange.

OEM Pole Assembly vs. Current Encapsulated Pole with Embedded Vacuum Interrupter
Figure 15

In addition to replacement VIs, many parts providers are now proving embedded pole replacements in place of the original pole assemblies for many breakers. While they are hard to fault, they are also more expensive than a standard pole assembly. However, when possible, embedded poles should be used for upgrades to the existing fleet of VIs in VCBs as they near the end of their service life. Embedded poles have taken over most of the world's new production VCBs as the new standard for the reasons listed in this paper.

Total Remanufacture: A Brand New Start

Breaker remanufacturing has traditionally been performed by the OEMs, but this has changed over the years and today customers have their choice between using the OEMs or other service companies for this work, and some even have in house overhaul programs. At a minimum, the remanufacture should include complete disassembly, cleaning, and lubrication of the operating mechanism and contact pivots. All of these overhaul steps must take in to consideration lubrication, evaluation, and availability of industry recommended replacements for each part. This "hardening" of the MVVCB has become so popular that some OEMs and service companies are beginning to offer these services for sale on new products for users to replace or exchange their legacy breakers. Tough duty breakers also boast more advanced plating to guard equipment for environmental issues, better insulating systems built with modern materials, and modern lubrication systems designed and tested for use on circuit breakers in the harshest environments. These modern tough duty direct replacement designs have longer warranties and essentially provide a total restart on the service life of the VCB.



Remanufactured Replacement Vacuum Circuit Breaker
Figure 16

The useful life of vintage MVVCBs can be extended and enhanced through the use of replacement parts and upgrades which utilize the technology of today rather than the technology available when the breaker was first introduced. All types of MVVCBs have issues that have been addressed by the OEMs with modifications and service upgrades. Older, outdated components are sometimes no longer produced and removed from product offerings, placing a tremendous burden on the customer to find suitable replacement parts. Quick delivery of replacement parts cannot be taken for granted and there are a large number of qualified suppliers which specialize in this industry who are knowledgeable about the engineering requirements for the equipment. As time moves forward, more and more emphasis will be placed on extending the service life of the valuable assets through component upgrades and remanufacture programs.

CONCLUSION

Based on the original criteria OEM marketing and sales departments gave product development and engineering teams, MVVCBs were only designed to have a 20 year service life. However, this does not mean that these MVVCBs will only last for 20 years – in fact many are now approaching 40 years of reliable service. But, what will it take to continue this trend and extend the useful life of the MVVCB fleet in the United States even further beyond their original life expectancy – say another 20, 30, or even 50 years? Yes, 50 more years of service is reasonable with proper consideration and planning, and this is really what is meant when discussing life extension – long term vision. The infrastructure in the United States is heavily dependent on MVVCBs in the intermediate distribution network for most applications. The MVVCBs in these applications will not simply be replaced – they will be coaxed to reach 100 year of service life by whatever means necessary. This may seem crazy to think about now only nearing the 50 year mark, but in the future others will be looking at how to reach the 100 year mark for this same equipment. The only way they will get to this point is if we continue to properly implement and improve existing life extension programs which put a priority on safety, reliability, and value.

One of the most important parts of a properly structured life extension plan for MVVCBs is adhering to an industry recognized maintenance philosophy. RCM is the preferred maintenance strategy endorsed by the industry standards due to its ability to utilize a combination of existing strategies and take advantage of their respective strengths to better understand all factors influencing maintenance intervals. In regards to specific maintenance intervals for MVVCBs, all sources point to a maintenance interval not to exceed five years, due largely in part to the limits of lubrication life. The maintenance testing should consist of accurately determining the interrupter’s remaining lifetime and also consist of verifying the breaker trip time. Continuous switchgear monitoring of insulation integrity and bus temperature is also beneficial to not only ensure breaker integrity but also ensure overall switchgear health. Asset owners can also benefit from non-OEM replacement parts and new technologies to extend service life and ensure reliable operation.

VI driven breaker technology has certainly fulfilled its promise from the past and will be around for decades to come. The technological advancements presented in this paper will become more and more essential for ensuring reliable operating longevity, and as time goes on there will be even newer and better breakthroughs to improve the reliability and monitor the condition of the entire system. Asset owners should always be thinking “What I can do to extend the usable life of my electrical system” and adopting these principles will go a long way towards meeting operational integrity goals. A more reliable system is a safer system, and that is really what this is all about – a protective system that will stand vigilant for many years, yet react quickly and do its job when called upon to do so.

REFERENCES

[1] L. T. Falkingham and G. Montillet, "A History of Fifty Years of Vacuum Interrupter Development (The English Connection)," in *IEEE Power Engineering Society General Meeting, 2004*, 2004.

[2] F. Ledbetter, J. Cadick, J. Day, F. Ledbetter, III, J. Toney and G. Garonzik, "Vacuum Interrupters: Pressure Versus Age, A Study of Vacuum Levels in 322 Service-Age Vacuum Breakers," 2016.

[3] T. Demaria, "Circuit Breaker Lubrication in the Field," *NETA World,* pp. 7-10, 2007.

[4] A. R. Salinas, B. Desai, J. Harley, B. Kinner and M. Lebow, "Circuit Breaker Mechanism Lubricant Performance Assessment: Investigation and Field Experience," in *82nd International Conference of Doble Clients*, Boston, 2015.

[5] B. H. Chudnovsky, "Lubrication of Electrical Distribution Equipment," *NETA World,* pp. 24-31, 2012.

[6] J. White, "Crital Maintenance for Circuit Breakers," *NETA World,* pp. 1-8, 2007.

[7] F. S. N. a. H. Heap, Reliability-Centered Maintenance, San Francisco: Dolby Access Press, 1978.

[8] J. Cadick, M. Capelli-Schellpfeffer and D. Neitzel, Electrical Safety Handbook, New York: McGraw-Hill, 2006.

[9] J. White, "Determining Maintenance Intervals for Safe Operation of Circuit Breakers," in *NETA PowerTest*, Denver, 2014.

[10] NETA (InterNational Electrical Testing Association); ANSI (American National Standards Institute), *MTS, Standard For Maintenance Testing Specifications for Eelctrical Power Equipment and Systems,* Portage: InterNational Electrical Testing Association, 2011.

[11] NFPA (National Fire Protection Agency), *70B, Recommended Practice For Electrical Equipment Maintenance,* Quincy, 2016.

[12] A. Greenwood, Vacuum Switchgear, London: The Institution of Engineering and Technology, 2007.

[13] H. Khan, A. Tjandra, H. Iu and V. Sreeram, "A Novel Island Detection Methodology for the Realization of Smart Grid," *Smart Grid and Renewable Energy,* pp. 330-337, 2011.

[14] J. Cadick, F. Ledbetter and A. Seidel, "Predicting the Remaining Life of Vacuum Interrupters in the Field," in *81st International Conference of Doble Clients*, Boston, 2014.

[15] P. G. Slade, The Vacuum Interrupter: Theory, Design, and Application, Boca Raton: CRC Press, 2008.

[16] B. Fenski, H. Fink, T. Fugel, D. Gentsch and T. Rumenapp, "Vacuum interrupters and embedded poles for medium voltage," *ETZ Elektrotechnik & Automation,* 2007.

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