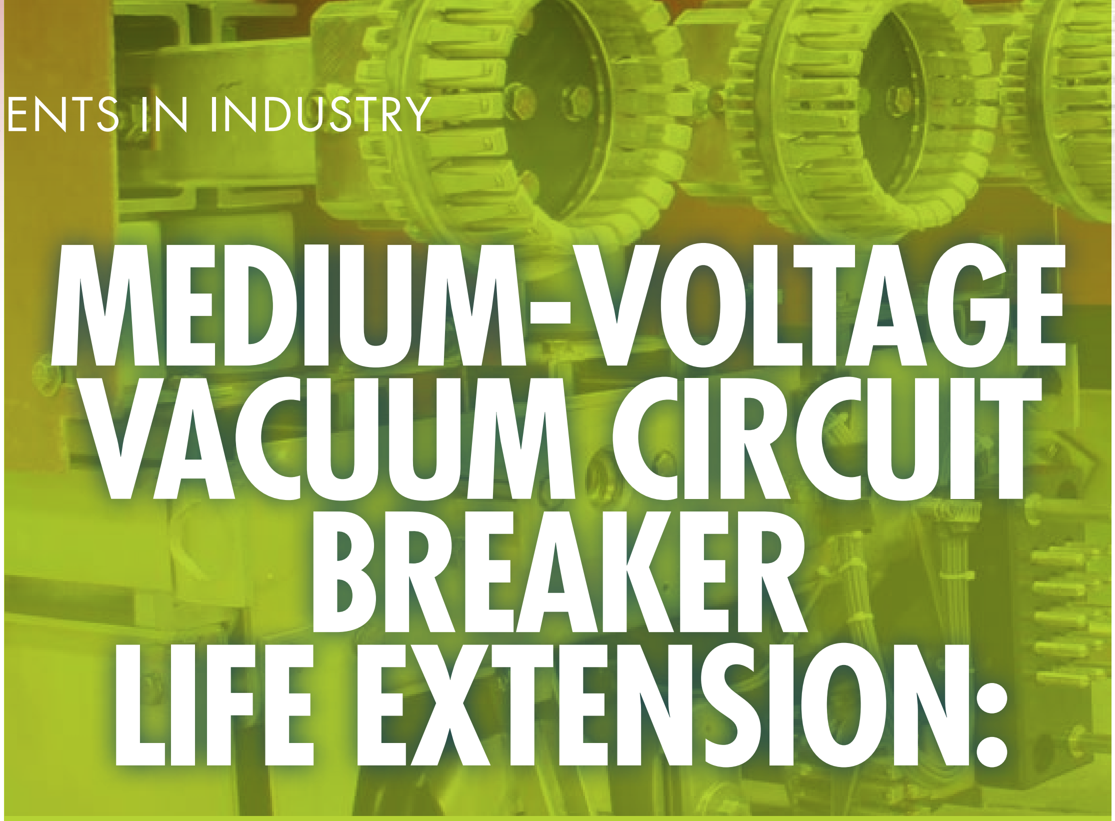

MEDIUM-VOLTAGE VACUUM CIRCUIT BREAKER LIFE EXTENSION:

A NEW APPROACH — PART 2

BY FINLEY LEDBETTER and DAVID WALTERSCHEID, *Group CBS, Inc.*

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. However, many of the medium-voltage vacuum circuit breakers (MVVCBs) in service today are nearing or exceeding their expected lifespan. This two-part paper provides evidence 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.

Part one, which appeared in the Summer 2018 issue of *NETA World*, discussed the properties and data that can offer a more accurate service life projection for breakers and described a three-tiered approach using industry standardized maintenance intervals and philosophies during the life of the equipment. This final section of the article describes newly available testing techniques and technologies to collect the data needed for an accurate service life projection for breakers, as well as component upgrades with replacements that can modernize the aging population of MVVCBs and keep these valuable assets in service for many years to come.

NEW TESTING TECHNIQUES

New developments in reliable, efficient test instruments and testing methods have made it possible to improve and re-evaluate historical methodologies. To minimize personnel injury, failures, and equipment damage, MVVCBs must be routinely tested and maintained to ensure proper function when called to action even after months or years of inactivity.

Wipe Spring Force

The energy stored in the closing springs of the circuit breaker mechanism provides a set amount of motion. The first portion of this motion is used to rapidly close the VI contacts. The remaining travel, known as wipe, is used to compress a preloaded spring (shown in yellow in Figure 1) to apply and maintain a constant force on the VI contacts while the breaker is closed.

Wipe has three main purposes:

- Compensate for contact erosion over time
- Maintain a low contact resistance
- Counteract the popping or blow-off force

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 the amount of wipe. Most technicians and service shops are aware of the effects of poor wipe due to contact erosion and resistance and know how to test for them. However, many are unfamiliar with arguably the most important purpose of wipe: counteracting popping force. The area actually touching between the VI contacts is quite small. As electric current flows through pinch points, an electromagnetic force, called a popping force, attempts to spread apart the VI contacts. This force can occur during high-current conditions, such as during faults.

Testing standards require VCBs to withstand full fault current for up to three seconds while the VIs remain closed. The strength of the popping force is proportional to the current passing through the contacts. Contact area will decrease as these points 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. Wipe spring force on the VI contacts can also cause problems, such as cracks in the contact faces, excessive bellows wear, and even bent poles.

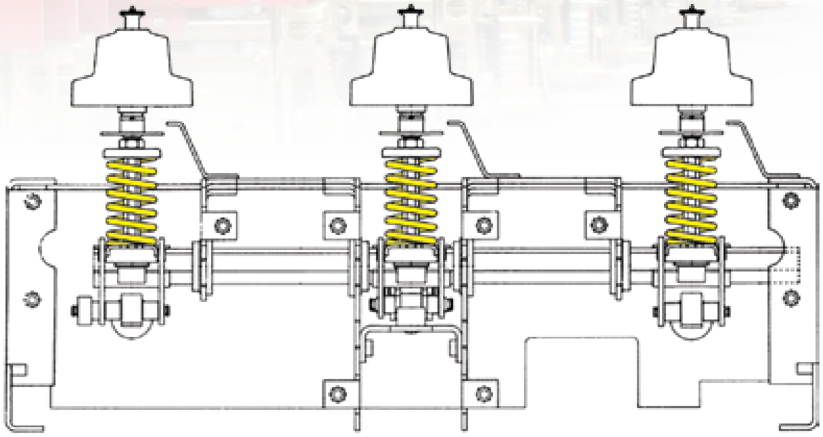

Figure 1: *Wipe Spring Placement on a Medium-Voltage Vacuum Circuit Breaker*

Figure 2: *Wipe Spring Rate Test Setup*

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. To get the poles of a breaker in sync, technicians 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, it is recommended that MVVCBs subjected to high temperatures for prolonged periods or high duty cycles have each spring removed and checked (similar to the test setup shown in Figure 2) to ensure the spring rate is within OEM specifications before returning to service.

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

MVVCBs and other electrical distribution switchgear all have an interrupting rating, 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 overcurrent protection device (OCPD) uses 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 computed as the sum of the circuit breaker's sensing time, unlatching time, and arcing time as demonstrated in Figure 3.

Arguably, the most important variable when performing incident energy calculations for an arc flash hazard analysis is the arcing time. It 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/cm2 at a specific working distance and used to select appropriate protective equipment and clothing for each piece of electrical equipment. 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 this changes or is inaccurate, the results of the arc flash study may put personnel in danger.

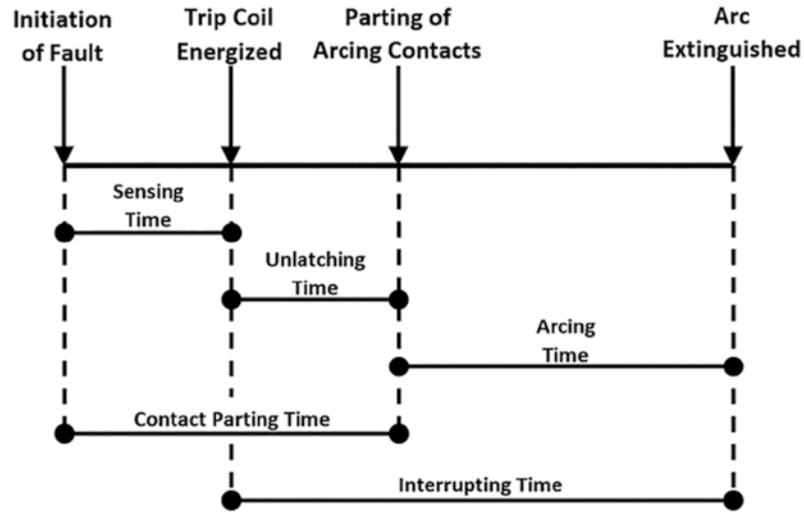

Figure 3: *Phases of Total Clearing Time in a Medium-Voltage Vacuum Circuit Breaker*

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.

Incorporating the timer and power supply into one unit can perform a circuit breaker time-travel analysis in a few minutes. Additionally, compatible secondary disconnect plugs are available to ensure users connect the device correctly to prevent damage to the breaker and/or tester. If a breaker cannot be removed, a vibration analysis will offer a chance to determine the overall mechanical condition and timing to ensure the equipment performs in accordance with 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 to minimize risk of having an unintentional time delay in MVVCB operation. Otherwise, extended clearing times could occur, and the time delay will adversely affect the results of flash hazard analyses. 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. With only parting time, what is really known about 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, data may be misinterpreted, potentially endangering service personnel.

Vacuum Interrupters: Predicting Their Remaining Life in the Field

A means of circuit protection is necessary 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 SF6 gas is due to vacuum's ability to interrupt high-energy faults quicker than the alternatives, thus improving personnel safety and equipment reliability. 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, three tests are used to validate their function prior to factory release:

- Contact resistance
- High potential withstand
- Leak rate

Only two of these have seen widespread use in the field: the contact resistance test and the high potential withstand test — neither of which can determine the level of vacuum pressure inside the VI. Only leak rate testing provides results beyond pass/fail, thereby offering quantifiable data about the integrity of the VI's vacuum pressure. Possessing data about the internal pressure would allow the use of reliability centered maintenance (RCM) procedures and programs, resulting in higher equipment uptime, longer lifecycles, and lower operating costs.

Until recently, leak rate testing has not been feasible for field applications due to equipment size, cost, and complexity. However, recent advances have enabled manufacturers to build portable leak rate test equipment.

Leak rate testing is based on the Penning Discharge Principle. Figure 4 shows the basic test setup for a VI leak rate test. 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, 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 known, the only variable remaining is the gas pressure. 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.

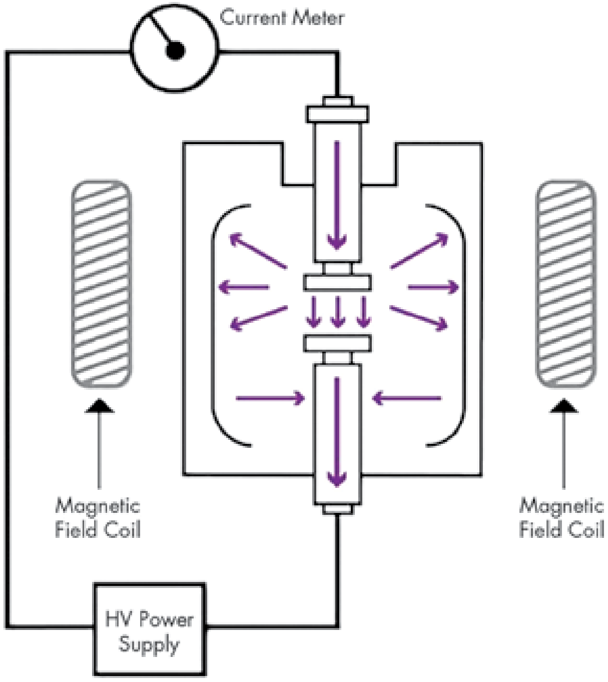

Figure 4: *Vacuum Interrupter Leak Rate Test Setup*

There will always be some leakage in even the best VIs, and leakage may be slow enough that the VI will meet or exceed manufacturer's predicted service life. To work efficiently, an RCM program depends on data gathered during testing. With continued adoption of leak rate testing, the electrical industry can see improvement in maintenance efficiency and a reduction in unexpected failures.

Continuous Partial Discharge Monitoring

Partial discharge (PD) is a localized dielectric breakdown within insulators due to voids, cracks, air bubbles, or foreign inclusions; it appears when the irregularity leads to a non-uniform electrical field in systems running under high-voltage stresses. Irregularities could be caused by internal, external, or 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 will occur as corona discharges, which are usually visible via a steady glow or arcing. Unmonitored PD events can become dangerous and will not cease without corrective actions. Over time, these effects will damage the insulation's integrity, as shown in Figure 5.

Figure 5: *Effects of Unmitigated Partial Discharge in Insulation*

Today's insulating systems have evolved. Advanced materials such as plastics, fiberglass, or epoxies will not be as sensitive to the environment and will last longer than previous materials, such as organic insulation, which was susceptible to moisture. Modern insulation materials can last 20 years and will far exceed this if kept clean and dry.

Many possibilities to detect and measure PD are available on the market and are widely used. Each is very site specific, as the switchgear environment and age of the equipment all dictate which method is applied. Continuously monitoring switchgear is possible by using electromagnetic field detection, which picks up the radio waves generated by PD events in insulation. This newly adapted technology is ideally suited for the most demanding applications, as when switchgear access is limited or maintenance is difficult and dangerous.

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 accurately assess the actual health of an insulation system, and the antenna and data acquisition instruments can also be used for interrogating surface acoustic wave-based, wireless, passive temperature sensors, thereby increasing value to the monitoring system.

Testing, for the sake of brevity, will be narrowed to the focus on ANSI/NETA MTS. Any reasonable attempt by maintenance personnel to meet this standard will put them well ahead of the rest of the world. The following tests should be done when performing maintenance on a MVVCB:

- Visual inspection
- Mechanical tests
- Electrical tests
- Mechanical/electrical test value comparison and analysis

Some of these tests were not available, nor were they accounted for when OEMs were designing these breakers to a specific service life. Today, the ability to perform these tests in the field has increased service life.

MODERN REPLACEMENT PARTS

In addition to regularly scheduled routine maintenance, MVVCBs may also require component upgrades to extend their service life. Facility managers must consider the initial capital cost, along with downtime during integration. The more cost-effective and environmentally friendly alternative is usually to leave the switchgear housing in place and upgrade all other parts of the existing VCBs and controls with the latest state-of-the-art replacement components.

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. For the foreseeable future, non-OEM vendors will have the necessary parts available to support legacy platforms.

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

With aging MVVCBs, VI failures are estimated to occur every few hours in the United States. New technologies and advances in material science, arc control, construction, and assembly have increased reliability and ratings, while decreasing the size and costs of VIs over the last half century (Figure 6).

One of the most significant improvements in VIs since their first use in VCBs has been contact materials. In a VI, contact material determines the properties of arc, current chop, its tendency to weld, and more. 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.

Figure 6: *Current Vacuum Interrupter with Improved Ratings vs. OEM Vacuum Interrupter*

An additional advancement is arc control contact geometry. Engineers had to address difficulties associated with interrupting high currents. When interrupting high currents, the arc is concentrated with all energy to a few spots on the contact surface, resulting in localized overheating, contact melting, and failure to interrupt. To solve this issue, engineers developed contacts that caused a self-induced magnetic field generated by the arc to help distribute the current more evenly; this aided in extinguishing the arc. These novel designs used a radial magnetic field; more recently, the technology evolved to feature an axial magnetic field to do so more efficiently. Better arc control geometries allowed the contacts to become smaller (Figure 7), which reduced the size and cost of VIs.

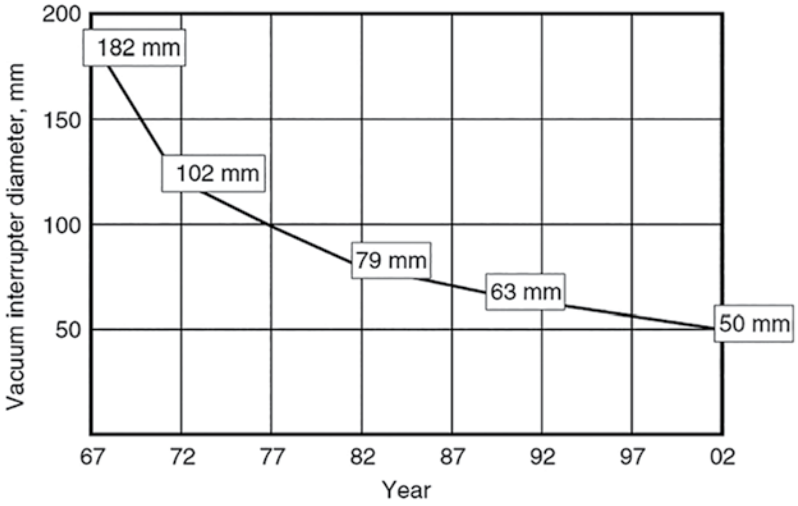

Figure 7: *15kV, 12.5kA Vacuum Interrupter Size Reduction over a 40-Year Timespan*

To take full advantage of the smaller VI contact, VI manufacturing methods needed to change. The pinch tube sealing method has now been replaced by a one-shot seal-off operation within a vacuum furnace. However, design options were still limited due to the need for a floating shield to prevent metal vapor produced during arcing. Adding complexity and cost, a shieldless VI was developed that used only one ceramic insulator with no metal vapor shield. This design drastically reduced the number of required components and simplified the assembly process.

These new manufacturing and assembly techniques have increased the shelf life for newly designed VIs. In addition, suppliers are providing upgraded components that offer these benefits, but may no longer be available from OEMs. When VI failure occurs, make sure to choose a modern VI to gain the benefits of almost a century's worth of research and development.

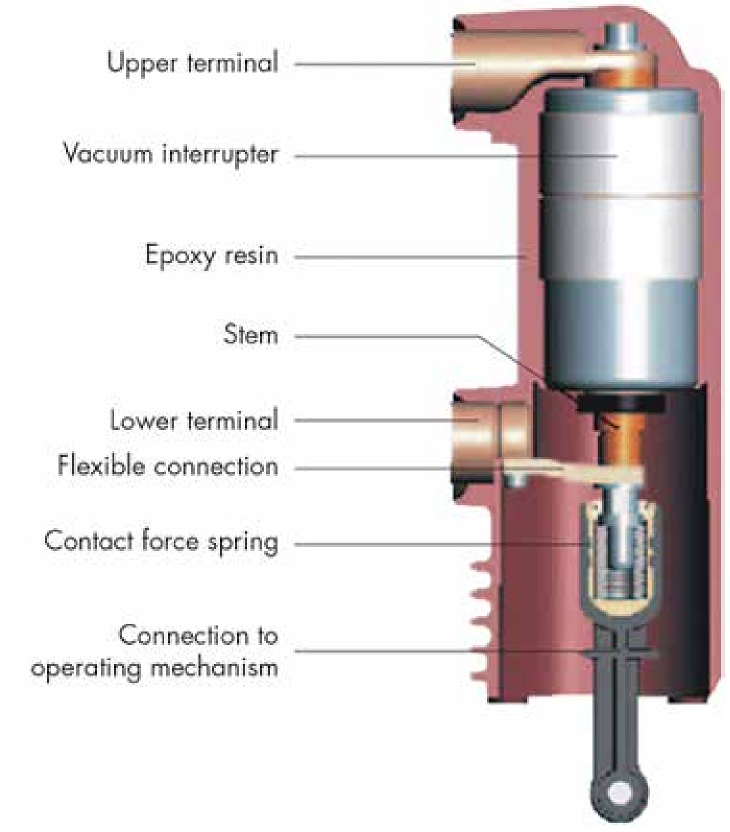

Figure 8: *Embedded Pole Construction*

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

The purpose of embedded poles 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 pole advantages include.

- High dielectric strength in air
- Suitability in a wide range of environmental conditions
- Increased structural rigidity
- Ability to seal and protect the VI from dust, moisture, and impact

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. Dielectric strength can be improved by embedding the VI in a solid silicone or epoxy resin (Figure 8), since the VI is protected from external contaminants and has an increased creepage distance. Recently, new epoxy formulations for outdoor applications boast qualities including:

- Lower moisture absorption
- UV resistance
- Improved thermal conductivity
- Higher impact strength
- Lower temperature limits down to -75 degrees F

This solution has been widely adopted for use in new IEC-rated MVVCBs and has been approved in ANSI-rated MVVCBs.

Because of their minimal maintenance requirements and compact robust designs, they are a promising solution for legacy VI pole assembly upgrades similar to those shown in Figure 9. Replacement assemblies must be ANSI/IEEE C37 tested and certified. When combined with proper mechanical maintenance of the breaker, these hardened and superior assemblies will extend the life of the equipment another 20-plus years. Embedded poles are close to the cost of a VI replacement with core exchange.

A Brand New Start

Breaker remanufacturing has traditionally been performed by OEMs, but today, customers have their choice between OEMs or other service companies. Some even have in-house overhaul programs. At a minimum, the remanufacture should include:

- Complete disassembly
- Cleaning
- Lubrication of the operating mechanism and contact pivots

During this remanufacturing process, the evaluation of individual parts should consider the availability of new industry-recommended alternative replacements. This evaluation and the upgrades that go along with it have become so popular that some OEMs and service companies are offering these hardened or tough-duty products to replace or exchange legacy MVVCBs. These offerings usually boast more advanced plating to guard equipment for environmental issues, better insulating systems 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 (Figure 10) have longer warranties and essentially restart the VCB's service life.

CONCLUSION

OEMs gave MVVCBs a 20-year service life. However, many are now approaching 40 years of reliable service. The infrastructure in the United States is heavily dependent on MVVCBs. The MVVCBs in these applications will not simply be replaced — they will be coaxed to reach 100 years of service life. It may seem crazy to think about this now, as we are only nearing the 50-year mark. However, it is achievable if we continue to properly implement and improve existing life-extension programs that prioritize safety, reliability, and value.

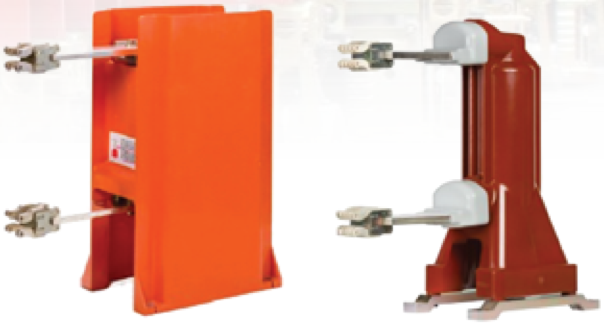

Figure 9: *OEM Pole Assembly (left) vs. New Encapsulated Pole with Embedded Vacuum Interrupter*

Figure 10: *Remanufactured Replacement Vacuum Circuit Breaker*

For MVVCB life extension, adhering to an industry-recognized maintenance philosophy is imperative; RCM is the preferred. Specific maintenance intervals for MVVCBs should not exceed five years, due largely to the limits of lubrication life. The maintenance testing should consist of accurately determining the interrupter's remaining lifetime and also 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 to ensure overall switchgear health.

Asset owners should always be thinking, "What can I do to extend the usable life of my electrical system?" Adopting these principles will go a long way toward 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 needed.

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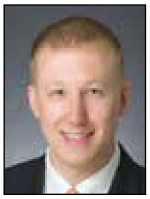
***Finley Ledbetter**, Chief Scientist for Group CBS, Inc., has over 40 years of power systems engineering experience. He is a member of IEEE and was a past president of PEARL. Finley was awarded NETA's Alliance Recognition Award at PowerTest 2016.*



***David Walterscheid** is currently a Senior Engineer at Group CBS, Inc. He started with Group CBS, Inc. in 2009 at CBS ArcSafe developing electrical safety equipment and served as Vice President of the company for over five years. David's patents in the field of remote operation for electrical equipment and the products he has developed have won awards from industry publications and organizations.*
