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Understanding Testing and Diagnostic Challenges Associated with Magnetically-Actuated Vacuum Circuit Breakers

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Abstract

There is a rich history of circuit breaker types and technologies. Whether we are referring to arc-extinction methods, such as oil, air-blast, air magnetic, SF6, and vacuum, or we are referring to energy storage methods, such as mechanical springs, pneumatics, and hydraulics, the use and preference of these technologies have changed vastly over time.

A newcomer, the magnetically-actuated vacuum circuit breaker, has entered the scene. This circuit breaker is found in the medium-voltage class, and eliminates the need for command coils, motors, and springs traditionally found in circuit breakers in this voltage class range. Instead, capacitors and a magnetic actuator are used in combination for the energy storage and delivery system. This change forces us to re-evaluate diagnostic testing specific to this circuit breaker. We now need to consider adding capacitor voltage and actuator current to our list of measured signals. Not only will these signals need to be measured, but also they will need to be properly analyzed.

From a technical maintenance perspective, these additional signals provide critical information about the proper function and condition of the magnetically-actuated vacuum circuit breaker.

This easy-to-follow paper and presentation focuses on the new challenges associated with testing and the diagnostic challenges associated with magnetically-actuated vacuum circuit breakers. The audience will be provided with an understanding, application, and analysis of these tests, supported by case studies.

Introduction

The selection of circuit breaker type and technology varies depending on the application. For medium-voltage applications, vacuum technology is widely used. In recent years, with the push to increase reliability and reduce maintenance, the control and operation methods of vacuum circuit breakers have also changed with the introduction of the magnetically-actuated vacuum circuit breaker. Command coils, latches, springs, and motors have been replaced by power supplies, capacitors, and magnetic actuators. This major change has reduced the number of moving parts. Manufacturers of these breakers are boasting that the magnetic mechanism can significantly outlast the vacuum interrupter itself.

Table 1, below, helps illustrate where the magnetically-actuated vacuum circuit breaker is classified as compared to all other circuit breakers. The properties of the vacuum circuit breaker with a magnetic actuator mechanism, highlighted in **RED** in Table 1, will be the main focus of this paper.

Table 1 – Circuit breaker classifications

BREAKER TYPES	MECHANISM TYPES
Bulk-Oil Circuit Breaker (OCB)	Mechanical (Spring)
Dead-Tank SF6 Breaker	Hydraulic
Live-Tank Air Blast	Pneumatic
Live-Tank SF6	**Magnetic Actuator**
Vacuum Breakers	
Air Magnetic	**INSULATION SYSTEMS**
Low-Voltage Air Blast	Oil
Reclosers	SF6
Circuit Switchers	Air
Sectionalizers	**Vacuum**

As it is with all breakers, we need to convert stored energy into mechanical movement. The fundamental difference in the magnetically-actuated vacuum circuit breaker is the energy storage element. Instead of applying the traditional energy storage methods, such as springs, hydraulics, and pneumatics, the magnetically-actuated vacuum circuit breaker deploys capacitors which store electrical energy in the form of joules.

Traditionally, we could see and hear the circuit breaker mechanism being charged by a motor. Now, with the magnetically-actuated vacuum circuit breaker, the mechanism is charged silently, as the capacitor system is charged. This silent charging operation, which is desirable, unfortunately, does not provide any clues or evidence that the unit is functioning properly. It is important that the capacitor system charges and discharges properly. Simple measurement signals can be added to the traditional timing test protocol that will monitor the function and integrity of the capacitor and actuator system.

Control Circuits

The control circuits for magnetically-actuated vacuum circuit breakers are a modern upgrade to traditional circuit breaker control schemes. Electronic circuit boards have replaced older, time-hardened electro-mechanical components, such as command coils and latches. These modern control circuits can be selected to operate at various voltages. In some cases, either AC or DC can be used; this makes them a good replacement option.

When connecting to a circuit breaker control circuit for testing, terminal block points 5, 7, and 9 are more often used than not, where 5, 7, and 9 are defined as (+)V, top of close coil, and top of trip coil, respectively. In traditional control circuits, actual volt-amperes (VA) are applied/injected to the command coils. However, when testing magnetically-actuated vacuum circuit breakers, only a “lower power” voltage signal is required. Instead, we need to interface with “Remote TRIP” and “Remote CLOSE” pins (5, 7, and 9) with the associated control board input points. These pins are defined in the instruction manual. Figures 1 and 2 illustrate the differences between the older style and newer control circuits. In this example, terminal block points 5, 7, and 9 are still relevant.

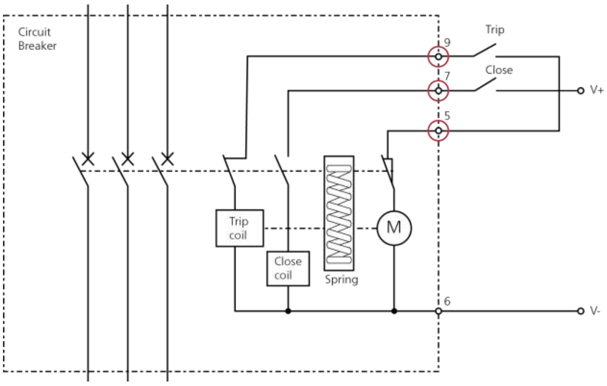

Figure 1 – Traditional control circuit

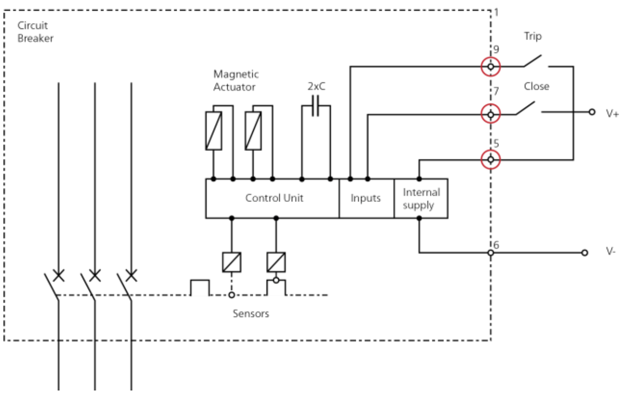

Figure 2 – Newer style control circuit

The command inputs, when energized, do not create the typical command coil current response. Instead, they are high-impedance voltage sensing inputs. Figures 3 and 4 show the differences in responses for traditional electromechanical command coils and the new high-impedance inputs.

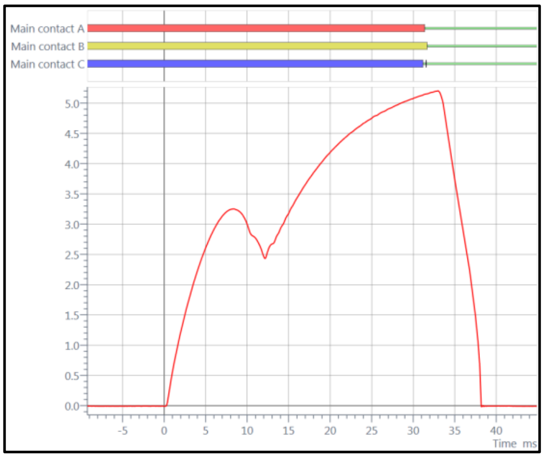

Figure 3 – Traditional coil current response

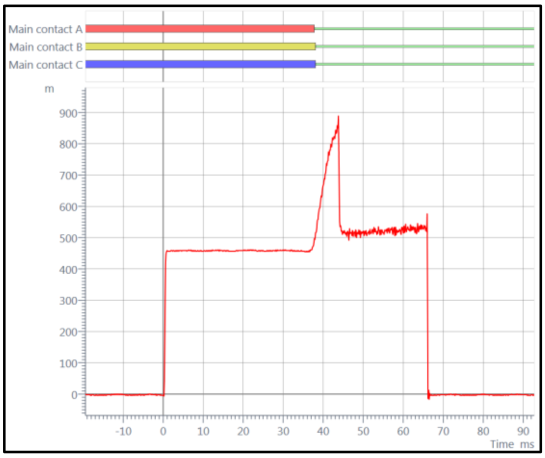

Figure 4 – High impedance input

These low-current responses may cause a threshold sensing issue for some test instruments. The test instrument must be able to accurately determine test initiation (t0+). It may be necessary to measure both the current and voltage applied to the command input.

Mechanism and Energy Storage

Because the magnetically-actuated vacuum circuit breaker stores electrical energy, it requires fewer moving parts. The primary components of the magnetically-actuated vacuum circuit breaker are as follows:

- Control Board
- Charger System
- Capacitor
- Magnetic Actuator
- Interrupter Assembly

Figure 5 shows the interrupter assembly of the circuit breaker.

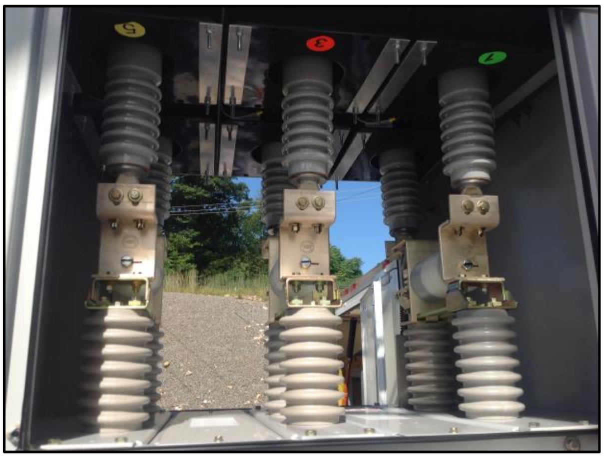

Figure 5 – Interrupter assembly of circuit breaker

Figures 6 and 7 show the Magnetic Actuator and Capacitor components, respectively.

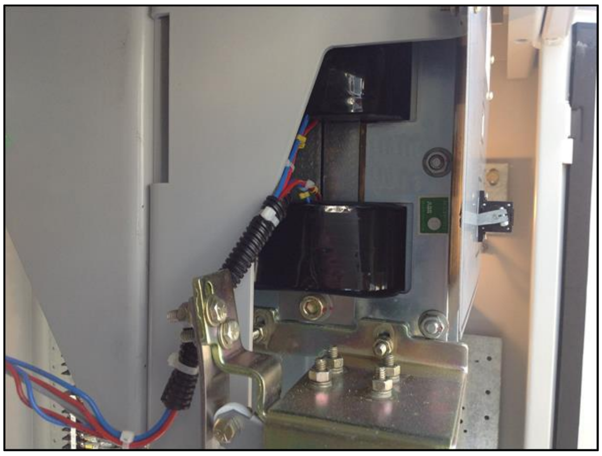

Figure 6 – Magnetic actuator (TRIP and CLOSE)

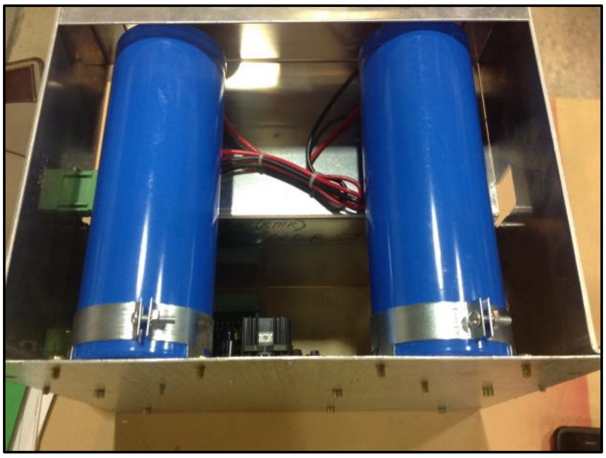

Figure 7 – Capacitors

Timing and Functional Testing

Circuit breaker timing and functional measurements consist of three steps:

1. Perform functional measurement
2. Calculate and analyze performance characteristics
3. Compare results to the manufacturer's recommendations or user-defined limits

Table 2 provides the fundamental tests and calculations involved in circuit breaker timing measurements and diagnostics.

Table 2 – Circuit breaker timing fundamentals

CONTROL	MEASUREMENT	CALCULATIONS
Trip (O)	Displacement	Main Contact Timing
Close (C)	Contact State (O-R-C)	Resistor Switch Timing
ReClose (O-C)	Command Coil Current	Delta Timing (Pole Spread)
TripFree (C-O)	Auxiliary Contact State (OW-OD-C)	Velocity
(O-CO)	Battery Voltage	Total Travel
(O-CO-CO)*	Phase Currents (First Trip)	Over Travel
Slow Close ©	Dynamic Resistance (DRM)	Rebound
First Trip (O)	Capacitor Voltage	Stroke
	Actuator Current	Contact Wipe
	Command Reference	Dwell Time (TripFree C-O)
		Dead Time (ReClose O-C)
		Capacitor Charging Rate
		Actuator Current Peak (O, C)
		Actuator Time (O, C)

* ANSI Operating Duty O-0.3s-CO-3Min-CO

Measured Signals

When performing circuit breaker timing and functional measurements, there are only four primary signals that are of interest.

1. Contact State (Open-Close)
2. Remote Input Signal (t0+) Command Reference: Start of Test
3. Capacitor Voltage
4. Actuator Current

Figure 8 illustrates a test that includes the measured signals listed above.

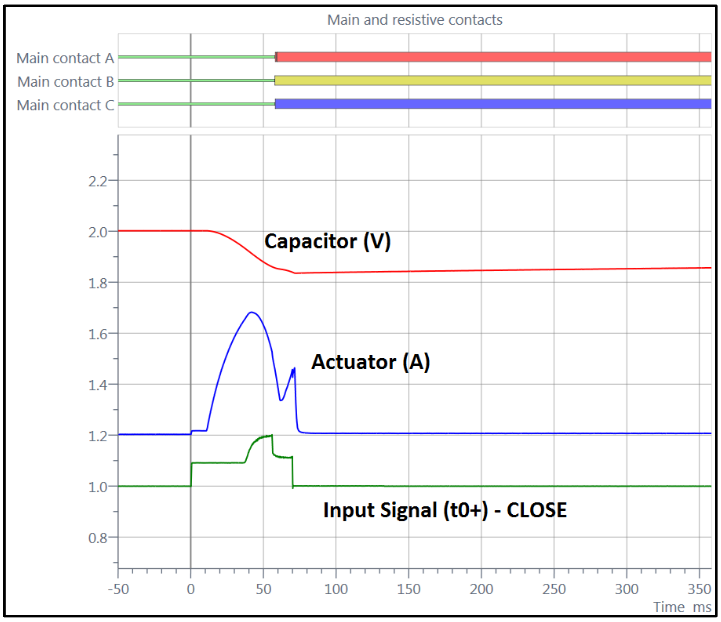

Figure 8 – Measured signals

It should be noted that the Capacitor Voltage will most likely be greater than the permissible touch voltage, so safety precautions shall be observed. It should always be assumed that the capacitor is charged. The Actuator Current is to be measured with a properly scaled Hall-Effect current clamp. Since the breaker only energizes one side of the actuator at a time, only one current clamp is required. Both the TRIP and CLOSE actuator wires can be measured by one current clamp. Practicality has shown that getting the correct polarity on the actuator wires is a function of trial and error. Having the wrong polarity will only invert the current waveform on the test instrument and not affect the test. Figures 9 and 10 illustrate the use of one Hall-Effect current clamp and the capacitor voltage measurement, respectively.

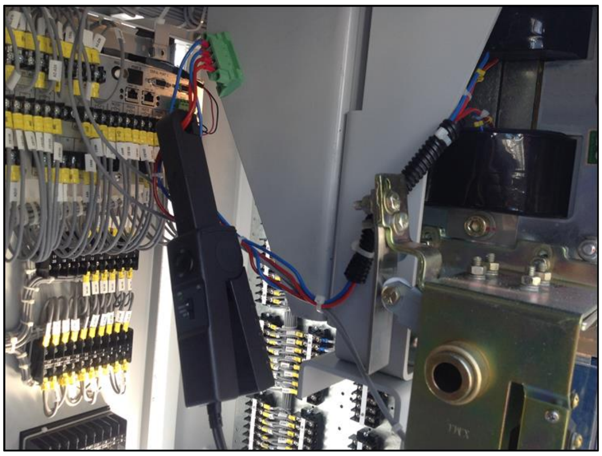

Figure 9 – Hall-Effect current clamp

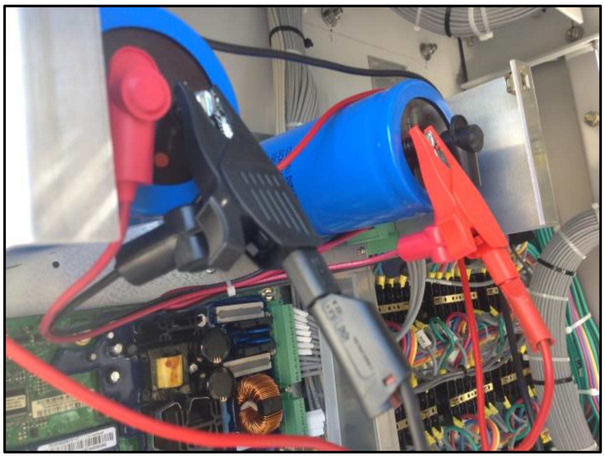

Figure 10 – Capacitor voltage measurement

Performance Characteristics

Table 3 lists all of the pertinent circuit breaker characteristics. There are seven in all, including four related to traditional timing, three related to capacitors and magnetic actuator.

Table 3 – Timing performance characteristics

Main Contact Timing	Time between test initiation (start of test) and change of main contact state (make or break).
Delta Timing (Pole Spread)	The time duration between first contact to change state and the last contact to change state, within a breaker, within a phase, or within a module.
Dwell Time (TripFree C-O)	The time duration that the main contacts remain open during the Trip-Free operation.
Dead Time (ReClose O-C)	The time duration that the main contacts remain closed during the Re-Close operation.
Capacitor Charging Rate	The steady rate at which the capacitors are charged after an operation. This will be a function of the capacitor voltage vs time, V/s.
Actuator Current Peak (O, C)	The peak current through the actuator for either a TRIP or CLOSE operation.
Actuator Time (O, C)	The time the actuator remains energized for either a TRIP or CLOSE operation.

Analysis of Results

Timing and functional test results are directly compared to the manufacturer's performance specifications and previous results [1]. All of the performance characteristics listed above will have pass/fail criteria. Table 4 illustrates typical performance characteristics. It should be noted that not all manufacturers document all performance characteristic limits; it may be worthwhile to baseline any missing limits with commissioning tests.

Table 4 – Typical performance limits provided by the manufacturer

Identification	CB1
Capacitor Voltage (steady state)	80 VDC
Capacitor Voltage (OPEN Threshold)	49 VDC
Capacitor Voltage (CO Threshold)	72.5 VDC
Capacitor Voltage (O-0.3-CO)	78 VDC
ANSI Operating Duty	O-0.3s-CO-3Min-CO
Interrupting Time	< 50 ms
Reclose Time (Dead Time)	300 ms minimum

Figures 11 through 14 show actual measurements for TRIP, CLOSE, TRIPFREE, and O-CO. Several features associated with the capacitors and magnetic actuators are calculated. Values such as capacitor voltages minimum, charging rate, actuator current peak, and actuator time are shown in these figures.

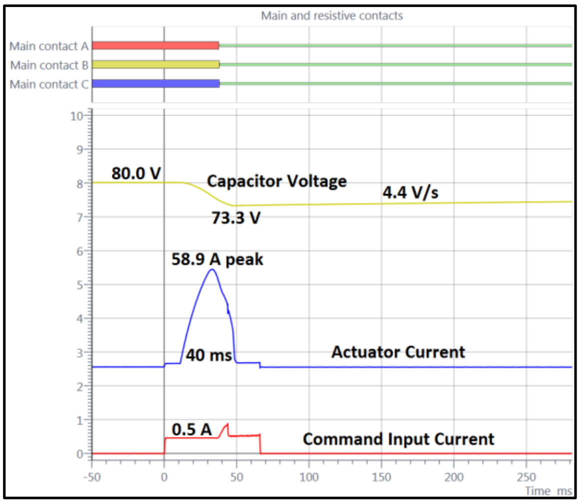

Figure 11 – OPEN

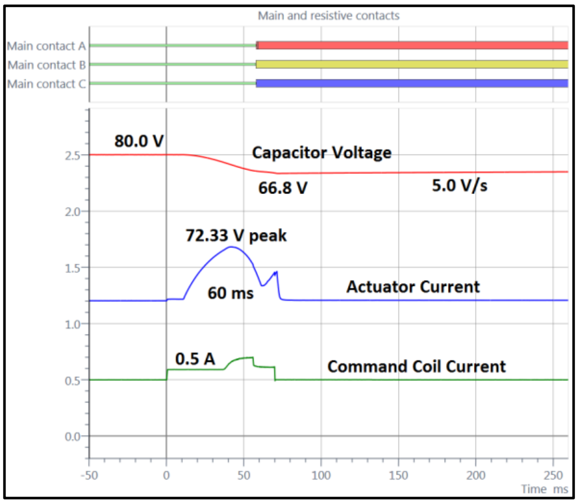

Figure 12 - CLOSE

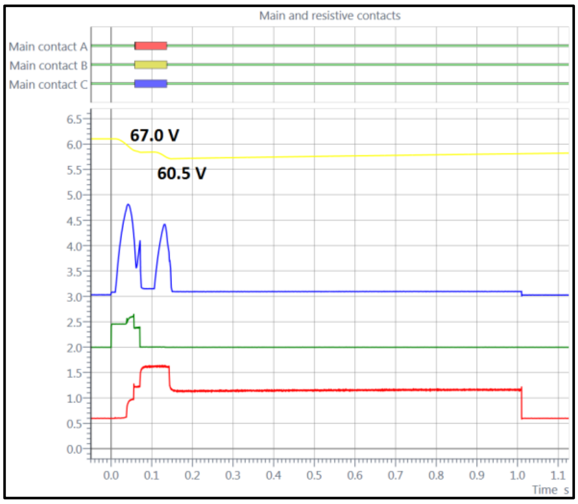

Figure 13 – TRIPFREE (CO)

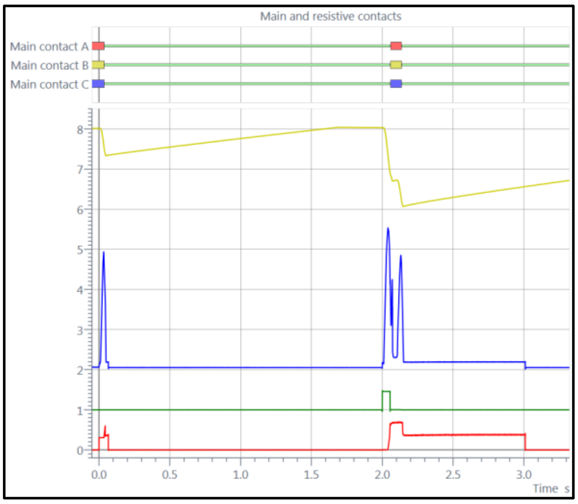

Figure 14 – OC-2.0-O

A few diagnostic indicators, such as contact bouncing can also be identified. In vacuum breakers, the contacts can experience discontinuities during the CLOSE operation. Figure 15 illustrates unusual bouncing of a main contact. In this example, dynamic contact resistance was recorded and presented to exaggerate this effect. It appears that the contact on phase A is not settling smoothly.

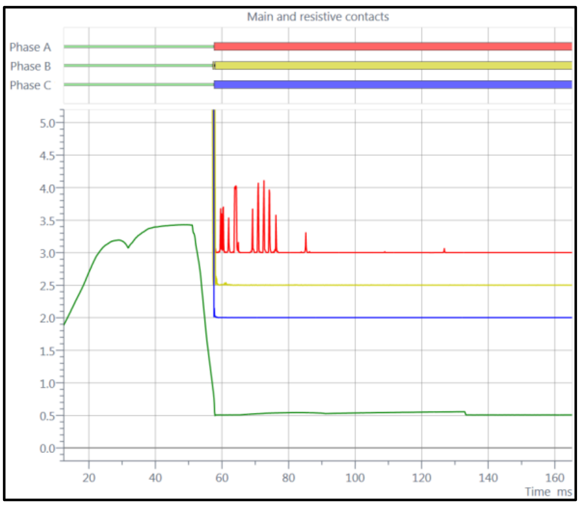

Figure 15 – Unusual contact bouncing

Contact Resistance

The micro-ohm measurement or static contact resistance measurement determines the continuity integrity of the main contact components. Abnormal readings may indicate improper alignment, pressure, or damaged contact surfaces, such as plating or coating.

This is the standard test that is performed to measure the actual resistance value of contact continuity and associated series components, such as bushing connections and tulips. The static measurement produces a single, temperature-dependent value in Ohms (Ω).

A static contact measurement is to be performed on each phase, using a DC current source. For vacuum breakers, typical measurements are less than 100 μΩ; however, the manufacturer's literature should be used to determine the actual expected value. Experience has shown measurements range from 10 μΩ to 100 μΩ depending on where this measurement is applied, i.e., directly across the vacuum bottles or from the bushing terminals. It is recommended to test across the bushing terminals. If higher than normal values are obtained, individual components can be isolated, and additional measurements performed. Figure 16 shows the selected lead placement directly across the vacuum bottles.

Figure 16 – Leads connected directly across the vacuum bottles

Table 5 lists typical static contact resistance results. It shows the differences between measurements performed directly at bushing terminals and across the vacuum bottles.

Table 5 – Typical Contact Resistance measurements

Across	Phase A	Phase B	Phase C
Terminals	100.02 μΩ	99.44 μΩ	99.15 μΩ
Bottles	28.40 μΩ	28.67 μΩ	26.72 μΩ

It is recommended that at least 100 A DC is injected for this test [2]. Also, it should be noted that if the breaker is equipped with CTs, it may take several seconds to saturate the opposing effects. Precautions should be taken to ensure that the injected high primary current does not affect protection circuits.

Conclusion

- Magnetically-actuated vacuum circuit breakers use capacitors to store the energy needed to operate the circuit breaker. This technique uses few moving parts, but is much different from traditional methods, such as spring, pneumatic, and hydraulic mechanisms.

- Control boards have replaced electro-mechanical TRIP and CLOSE coils. Volt-Amperes are no longer needed to drive these command coils. Instead a voltage signal is applied across a high-impedance input.

- It is now recommended to add capacitor voltage and actuator current to the list of measured signals for performance and functional testing. These signals provide information for verifying the integrity of the charging system, capacitors, and magnetic actuator.

- Three new performance characteristics are generated from the capacitor voltage and actuator. They are capacitor charging rate, actuator peak current, and actuator time. Presently, standards and recommended values do not exist for these performance characteristics. However, they are most likely to become very popular once more experience is gained with these breakers.

References

[1] ANSI/NETA MTS-2011, "Standard for Maintenance Testing Specifications for Electrical Power Equipment and Systems"

[2] P. Gill: "Electrical Power Equipment Maintenance and Testing" *Second Edition,* CRC Press, 2009

Charles Sweetser received a B.S. Electrical Engineering in 1992 and a M.S. Electrical Engineering in 1996 from the University of Maine. He joined OMICRON electronics Corp USA, in 2009, where he presently holds the position of PRIM Engineering Services Manager for North America. Prior to joining OMICRON, he worked 13 years in the electrical apparatus diagnostic and consulting business. He has published several technical papers for IEEE and other industry forums. As a member of IEEE Power & Energy Society (PES) for 15 years, he actively participates in the IEEE Transformers Committee, where he held the position of Chair of the FRA Working Group PC57.149 until publication in March 2013. He is also a member of several other working groups and subcommittees. Additional interests include condition assessment of power apparatus and partial discharge.

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