Condition-based monitoring of oil-insulated, vacuum interrupting single-phase reclosers

Effective:
September 2017
Supersedes:
April 2014

Michael Culhane
Reliability and Test Manager—Switchgear
Eaton

Industry trends

Recent surveys show that utilities continue to scrutinize maintenance budgets for sources of operating cost savings. Historically, utilities established time-based maintenance cycles based on their operations experience, operating environment, and manufacturer's recommendations. Utilities are increasingly deploying condition-based monitoring (CBM) for establishing maintenance cycles for their assets [1]. CBM is considered the most efficient and effective method for users to determine the need for maintenance or replacement of equipment. This started with transmission assets and is transitioning to equipment installed on distribution systems. Utility interest in CBM for line-installed reclosers has increased as the number of installed units and their age increases.

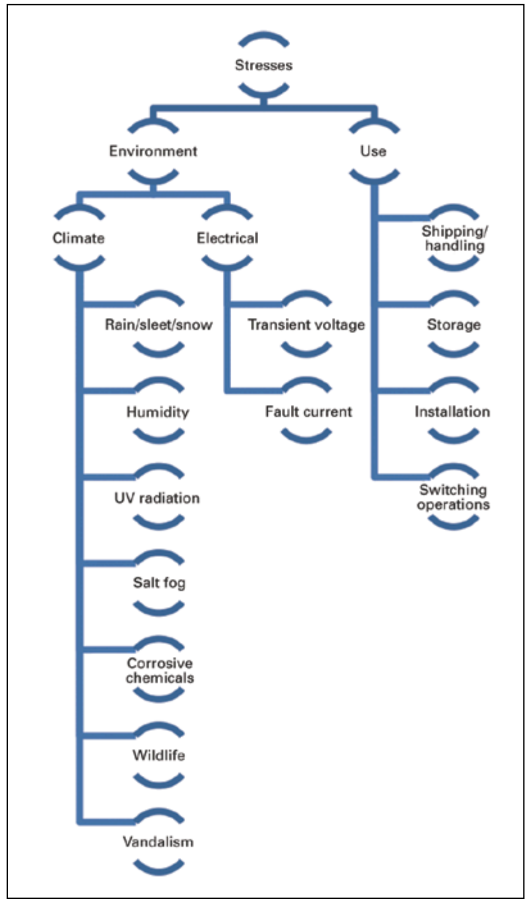
Eaton offers a family of Cooper Power™ series reclosers that are elegantly simple yet contain design features that withstand environmental and use stresses, significantly extending condition-based maintenance cycles. The purpose of this paper is to provide insight on CBM techniques that can be applied to oil-insulated, vacuum interrupting single-phase reclosers by examining stresses that drive recloser wear-out and the design features that address those stresses.

Outdoor electrical equipment stresses

Electrical equipment installed outdoors is subjected to environmental and use stresses that may degrade performance.

The impact of these stresses on the maintenance cycle of the product is a function of the robustness of the design. This is assessed by the manufacturer using a combination of tools:

- Fault tree analysis (FTA)
- Potential failure mode effects analysis (PFMEA)
- Reliability tests
- Failure reporting, analysis and corrective action system (FRACAS)
- Service center feedback
- Customer studies



Analysis of this data reveals wear-out modes that fall into two distinct classifications: detectable and non-detectable. Detectable wear-out modes are those that can be observed by the user as part of a routine inspection program or through normal interface with the device. These include:

- Mechanism wear—operation counter exceeds 2500 operations
- Corrosion—bleeding rust, oil stains on tank
- Wildlife damage—nesting materials near bushings
- Vandalism—oil stains on tank, gunshot holes
- Bushing flashover damage—lightning arrester isolator and ground strap separated from arrester body

Critical non-detectable wear-out modes are:

- Insulation system—degradation of dielectric strength of oil
- Vacuum interrupter—degradation of dielectric strength, loss of contact pressure due to contact erosion

EATON
Powering Business Worldwide

Previous recommendations for monitoring and assessing the dielectric strength of the oil involved obtaining oil samples at fixed time intervals. Vacuum interrupter wear-out has historically combined data from the operations counter with extrapolations based on interrupter duty testing. A more accurate method of assessing vacuum interrupter wear that builds on previous techniques and reveals a substantially longer life is discussed below.

A closer examination of the insulation system design of oil-insulated, vacuum interrupting single-phase reclosers reveals a system that actively manages water content. This work is discussed below and includes testing of worse-case water accumulation to verify dielectric integrity.

Oil-insulated single-phase reclosers

Oil-insulated single-phase reclosers are an affordable and highly reliable system protection device. For oil interrupting reclosers (arc interruption occurs under oil), the maintenance cycle is primarily driven by the degradation of the oil's dielectric properties due to accumulation of carbon and other arc byproducts in the oil. The industry transition to oil-insulated, vacuum interrupting reclosers (arc interruption occurs in a vacuum bottle) eliminates the byproducts in the oil and significantly reduces the risks associated with oil degradation.

Oil-interrupting design features:

- Substantial dielectric clearances (to withstand the effects of deteriorating oil due to arc interruption under oil)
- Vented tank (to vent gasses generated from arc interruption under oil)
- Paper desiccant (to stabilize the relative saturation of the oil during cool-down after lock-out)

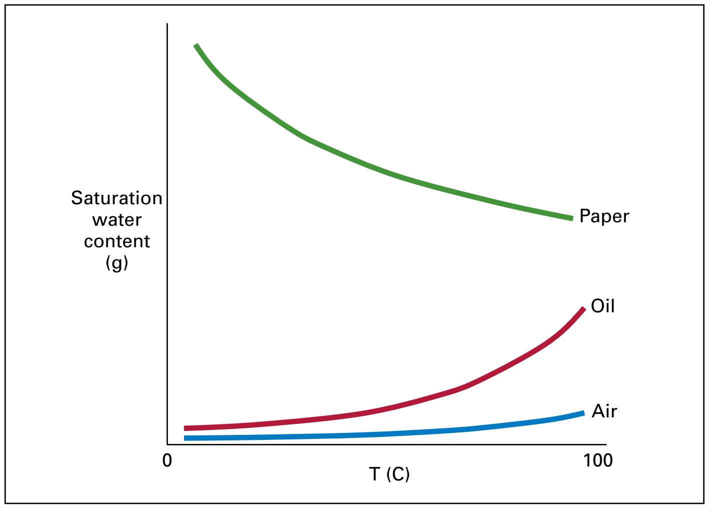
Vacuum interrupting design features:

- Arc interruption occurs in the vacuum bottle—no byproducts contaminate the oil
- Dielectric clearances for the oil interrupting design are retained for the vacuum design, increasing design margin
- Vented tank for the oil interrupting design is retained for the vacuum design, minimizing stress on gaskets
- Paper desiccant for the oil interrupting design is retained for the vacuum design, stabilizing the relative saturation level of the oil

Eaton's Cooper Power series Types V4H, V4L, and V4E are mineral oil-insulated, vacuum interrupting reclosers that share many design features with the oil-insulated, oil-interrupting H, L, and E reclosers. Among these is a vented air space above the oil.

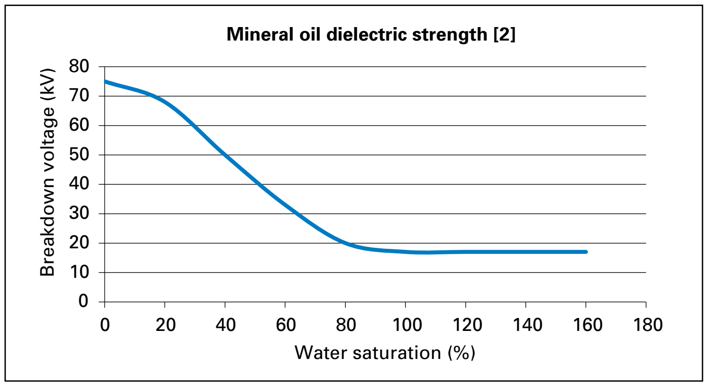
This is an essential design feature for the oil-interrupting device because arcs drawn under oil during current interruption generate gas pressure that must be equalized. The vented air space allows an exchange with ambient air. Both oil interrupting and vacuum interrupting designs include high-density paper for the purpose of managing moisture changes due to the vented tank. A detailed look at the vented air, oil, paper insulation system reveals how this system works in concert with dielectric clearances to eliminate risk of dielectric breakdown due to changes in oil moisture content.

The primary insulation system of these reclosers is mineral oil. However, the vented head space air and a high-density paper liner play important roles in managing the moisture content of the oil. This system of air, oil, and paper has been intentionally designed such that changes in relative moisture levels of the oil and air are compensated by the moisture capacity of the paper. As applied in the V4H, V4L, and V4E reclosers, these materials have the following relative moisture capacity relationship with temperature.



In a stable environment (constant temperature and moisture), all materials will seek equilibrium to the same relative saturation point. As temperature increases, moisture will move from the paper to the oil and then to the air. In the vented air space system, the moist head space air will seek equilibrium with the outside ambient air. As temperature decreases, moisture in the oil will be absorbed by the paper as the process reverses [2][3].

Managing the relative saturation level of the oil is important because the dielectric strength of the oil varies with its relative saturation level.



The dielectric integrity of the recloser depends on two key design elements: the moisture management system described above and adequate dielectric clearances of oil-insulated electrical parts within the tank.

To illustrate the moisture management system, **Table 1** lists the water concentration within the V4L/V4E for various application scenarios. The first represents factory level conditions. The second represents storage in a high ambient temperature and relative humidity environment. The last is at rated load current in a warm ambient environment.

Table 1. Water concentration V4L/V4E (steady state)

T (C)	Relative sat. level	Air (g)	Oil (g)	Paper (g)
20°	70%	0.05	1.3	51
40°	90%	0.19	3.7	60
60°	80%	0.42	6.7	50

A typical operating scenario may involve a recloser carrying rated load current, cycling to lock-out in response to a permanent fault, and then cooling to ambient. In this scenario, the moisture absorbed while hot will cause the relative moisture level of the oil to increase dramatically as the recloser cools, resulting in a significant drop in dielectric strength.

The recloser design anticipates this drop in dielectric strength through increased spacing between energized parts and ground, ensuring adequate dielectric strength until the water in the oil can be absorbed by the paper desiccant.

To verify the scenario above, a V4E recloser sample (27 kV, 100 A coil, 2A/2B timing) was deliberately forced into a high relative saturation scenario and tested. The sample had initial measured water content in oil of 10 ppm (approximately 0.72 g of water). Assuming equilibrium between oil and paper, the initial water content of the paper was calculated to be approximately 13.0 g. To emulate equilibrium when hot (60 °C, 80%RS) the water content of the oil would need to be increased to 6.7 g and the paper water content would need to increase to 50 g. To ensure saturation after cool-down, 50 g of water was added to the oil. To promote absorption, the unit was heated and water added in two steps (before and after heating).

The sample was then cooled to room temperature and subjected to rated BIL and rated ac withstand testing. Testing was conducted in the open contact position from both the load and source side terminals to ensure all current-carrying parts were stressed to ground. The results of the testing demonstrate that the internal (under oil) dielectric clearances of the V4E reclosers are sufficient to withstand rated BIL and ac withstand voltage stresses after the dielectric strength of the oil has been reduced. Similar testing was successfully completed on V4H and V4L samples.

The results of this testing verify that the oil, air, and paper desiccant system in concert with generous internal conductor spacing mitigates risks associated with moisture accumulation from water vapor.

Chemical degradation of the oil (oxidation) poses a significant concern in transformer applications but the risks are far lower in switchgear. Oxidation is a function of time and temperature, and the moderate oil temperature rise in switchgear (typically 30 °C) results in a slow thermal aging rate. Degradation may affect many important oil properties (e.g., viscosity, specific gravity, flash point, total acid number, breakdown voltage, dissipation factor, and volume resistivity). While no industry-wide consensus has been reached on which property defines end-of-life (EoL), they all agree that the reaction rate is slow at 60 °C [4][5].

**Table 2. Oil oxidation
(30 °C ambient + 30 °C average oil rise = 60 °C)**

Oil property	EoL criteria	EoL
Volume resistivity [4]	1.5×10^{11}	37.6 years
Loss factor [4]	50	38.4 years
Acidity [5]	0.3 mg KOH/1 g oil	28.5 years

Contact wear

Another important consideration in determining the health of the recloser is assessing contact wear. With each electrical operation of a vacuum interrupter, metal from the surfaces of the contacts is vaporized. The amount of metal is a function of vacuum interrupter design and the amount of current being interrupted. The metal vapor condenses on the interior surfaces of the vacuum interrupter and can eventually degrade dielectric strength. The loss of metal from the contact surfaces also affects the mechanism by changing the amount of energy stored in the contact pressure spring. The V4H, V4L, and V4E mechanisms have been designed to provide adequate contact pressure with up to 3 mm of contact wear.

Assessing the wear of the vacuum interrupter contacts poses the challenge of measuring contact erosion and metal vapor deposition in a sealed vessel. A non-invasive alternative is the use of vacuum interrupter life test results to estimate the maximum number of operations for a given series coil current rating. Numerous interrupter duty test programs have been conducted on these products since first being introduced in the 1980s.

The data from these programs is used to correlate operations counter readings to remaining life based on the magnitude and frequency of faults.

Eaton recommends the time integrated current method to establish the contact life of vacuum interrupters [6]. The time integrated current is calculated based on contact part at current peak and fault clearing at first current zero crossing. The number of interruptions at various current levels and the cumulative integrated currents for the V4L and V4E recloser are shown in **Table 3**.

Table 3. Interruptions at various current levels

Test current as a percent of rated interrupting current	8 kA interrupter duty ①	12.5 kA accelerated interrupter duty ①	24 kA accelerated synthetic circuit interrupter duty
20%	88	88	80
33%	0	101	81
50%	112	81	106
67%	0	16	83
83%	0	0	85
100%	32	36	88
Cumulative integrated current (kA)	2.37	6.5	54.5

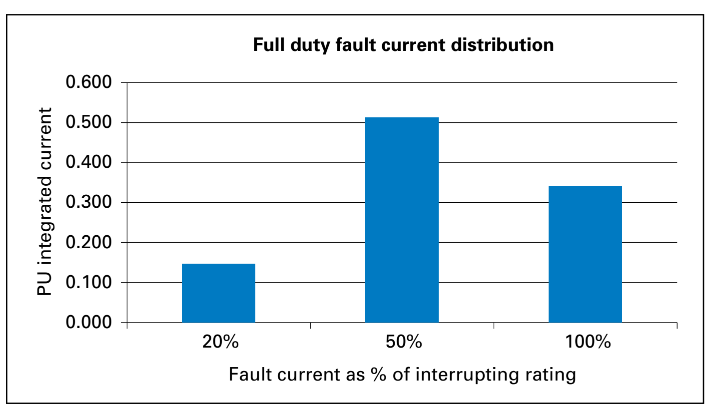
① Extensive fault testing meets twice half life of vacuum interrupter as defined by IEEE® Std C37.60™-1981 standard. Following this testing, all samples passed post-duty electrical testing.

For the V4H recloser, interrupting duty testing of the vacuum bottle demonstrated a minimum life of 1.07 kA of time integrated current.

It is important to note that due to test lab availability and time, none of these tests resulted in contact end of life. All samples passed post-duty electrical testing. Even so, the data is sufficient for the user to calculate the number of operations to estimated end of life based on fault current magnitude scenarios.

Faults occurring on overhead power systems protected by reclosers have fault impedances that vary by the conductivity and nature of the fault. The criteria for contact life, including the distribution of the number of faults and their current levels, was established by the working group members of IEEE Std C37.60-1981 standard. Presumably, these criteria represent the operating practices of the utilities that reference the industry standard in their product specifications. Cumulating integrated current for each test level from IEEE Std C37.60-1981 standard Table 6 and converting to per unit basis results in the graph below.

This near normal (Gaussian) statistical distribution is reasonable for reclosers installed at locations where available fault current is at or near nameplate rating. This information can be consolidated into scenarios that allow the user to determine contact life by monitoring the operations counter for the scenario most appropriate to the application.



V4L and V4E contact assessment scenarios

Scenario 1 is the most conservative. It utilizes the cumulative integrated current from the 8 kA duty testing and assumes all operations are at the maximum rated fault current of the device.

Scenario 2 utilizes the cumulative integrated current from the 8 kA duty testing and assumes that fault magnitudes and frequencies are distributed similar to those from the duty tests specified in IEEE Std C37.60-1981 standard.

Scenario 3 uses the cumulative integrated current from the 12.5 kA accelerated duty testing and assumes that fault magnitudes and frequencies are distributed similar to those from the duty tests specified in IEEE Std C37.60-1981 standard.

Scenario 4 utilizes one-fourth the cumulative integrated current from the 24 kA accelerated synthetic duty testing (a value selected based on other studies that correlate the synthetic test results to power test results) and assumes that fault magnitudes and frequencies are distributed similar to those from the duty tests specified in IEEE Std C37.60-1981 standard.

Table 4. V4L and V4E scenario data

Coil rating	Maximum interrupting	Maximum number of operations			
		Scenario 1	Scenario 2	Scenario 3	Scenario 4
15	0.9 kA	685	1533	2500 ①	2500 ①
25	1.5 kA	411	920	2500 ①	2500 ①
35	2.1 kA	293	661	1813	2500 ①
50	3.0 kA	206	459	1260	2500 ①
70	4.2 kA	147	327	898	1796
100–280	6.0 kA	103	232	629	1259

① Vacuum interrupter life is constrained to mechanism life of 2500 operations.

V4H contact assessment scenarios

Scenario 1 is the most conservative. It utilizes the cumulative integrated current from the 2 kA duty testing and assumes all operations are at the maximum rated fault current of the device.

Scenario 2 utilizes the cumulative integrated current from the 2 kA duty testing and assumes that fault magnitudes and frequencies are distributed similar to those from the duty tests specified in IEEE C37.60.

Table 5. V4H scenario data

Coil rating	Maximum interrupting, 15.5 kV	Maximum number of operations	
		Scenario 1	Scenario 2
5	0.2 kA	1384	2500 ①
10	0.4 kA	692	1452
15	0.6 kA	461	968
25	1.0 kA	277	581
35	1.4 kA	198	415
50–200	2.0 kA	138	290

① Vacuum interrupter life is constrained to mechanism life of 2500 operations.

Some users have observed that the operations counter typically includes the operations conducted during production testing and commissioning. Routine maintenance of the overhead distribution system may also increase the count. These “counts” are not included in the above analysis.

Conclusions

Condition-based monitoring techniques can be successfully applied to oil-insulated, vacuum interrupting reclosers through routine visual inspection of installed product.

Eaton’s Cooper Power series V4H, V4L, and V4E vacuum interrupting, hydraulically controlled reclosers’ time proven design eliminates wear-out failure modes found in sealed tank designs. These reclosers share mechanisms, insulation systems and design clearances with their oil interrupting forefathers, providing additional design margin and robustness.

The combination of oil, paper desiccant, and free breathing tank actively manages moisture content of the oil over the recloser operating life. This analysis confirms anecdotal evidence presented by customers that maintenance cycles can be extended beyond previous recommendations.

Operation counts combined with a user-selected application scenario provides an easy-to-use method for determining the maintenance intervals for these reclosers.

Utilizing the above scenarios allow the user to establish condition-based maintenance schedules, often exceeding 15 years.

Biography

Michael P. Culhane, reliability and test manager for switchgear products, Power Systems Division at Eaton, has been with the company for 30 years. During this time he has held various roles spanning application engineering, custom products engineering, product development, project and program management and product reliability. Michael has a BS in electrical engineering from Marquette University and is a member of IEEE PES, a PMI certified Program Management Professional, and a licensed Professional Engineer in the state of Wisconsin.

References

[1] R. Bush, “Maximizing Our Aging Transmission and Distribution Assets”, Transmission and Distribution World, November 18, 2013.

[2] A. Pondes, E. de Meulemeester, et al, “Water Absorption by Oil in MV Switchgear”, 20th CIRED International Conference on Electricity Distribution, June 2009.

[3] Y. Du, M. Zahn, B.C. Lesieutre, A.V. Mamishev, “Moisture Equilibrium in Transformer Paper-Oil Systems”, IEEE Electrical Insulation Magazine, January/February 1999, Fig 10.

[4] L.V. Badicu, L.M. Dumitran, P.V. Notingher, R. Setnescu, T. Setnescu, “Mineral Oil Lifetime Estimation Using Activation Energy”, 2011 IEEE International Conference on Dielectric Liquids.

[5] M.R. Meshkatoddini, S. Abbospour, “Aging Study and Lifetime Estimation of Transformer Mineral Oil”, American Journal of Engineering and Applied Sciences, 2008, pp 384–388.

[6] P.N. Stoving, J.F. Baranowski, “Interruption Life of Vacuum Circuit Breakers”, Proceedings IEEE 19th International Symposium on Discharges and Electrical Insulation in Vacuum, Xi’an China, 2000, pp. 388–391.

Powering Business Worldwide

Eaton
1000 Eaton Boulevard
Cleveland, OH 44122
United States
Eaton.com

Eaton’s Power Systems Division
2300 Badger Drive
Waukesha, WI 53188
United States
Eaton.com/cooperpowerseries

Printed in USA
Publication No. WP280001EN / Z19970
Supersedes WP280-14049
September 2017