

Advanced Condition-Based Maintenance in Hydro Generation Power Plants: Powerful Visual Training

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Abstract

Historically, the maintenance of electrical equipment supporting hydro generation plants was scheduled according to manufacturer's recommendations and general "rule of thumb". Maintenance schedules evolved from two-year checkups to upwards of 10-year maintenance plans that overlooked areas that caused major outages. In reality these plans need to account for operating conditions and power generation equipment upgrades so as to ensure personnel safety and the reliability of equipment.

Unfortunately, maintenance does not have a one-size solution. However, interactive educational tools can simplify the maintenance of circuit breakers, the basic building blocks of power distribution systems in hydro generation plants. Through a digital educational program, operations and maintenance personnel can optimize equipment performance and identify equipment that requires attention to extend the useful life of generation assets and enhance the performance of aging power systems.

This presentation will discuss ways to address workforce knowledge gaps and optimize critical equipment performance for hydro generation power plants. An interactive presentation will provide visual, step-by-step training for circuit breaker maintenance that will enable operations and maintenance personnel to identify conditions that indicate maintenance may be required and/or that equipment may need to be recalibrated.

Specific operating conditions for hydro generation facilities and changes therein will be discussed and repercussions for maintenance programs will be identified. These will include: exposure to humidity, changes in temperature, partial discharge in insulations systems, general circuit breaker maintenance, record keeping and upgrades to turbines and other changes in equipment conditions and expectations.

Introduction

Electrical maintenance intervals in hydro generation plants for power circuit breakers and bus conductor systems range from less than two years to more than ten years. Service records can be limited or non-existent and reviews of maintenance procedures yield little or no quantitative measures to justify corrective action. This makes it difficult to establish the interval for the next maintenance period. Maintenance intervals that are too short and involve many processes increase the facility's maintenance costs disproportionately to the improvement of performance or reliability. Maintenance intervals that are too long and have very few processes tend to lower the facility's maintenance costs while opening the door for major failures of power circuit breakers and associated equipment. A compromise between maintenance intervals and required procedures based on specific measurement criteria and historical industry feedback may yield better performance and overall cost control. Reliability Centered Maintenance (RCM) is an offshoot of Conditioned Based Maintenance (CBM). RCM uses diagnostics and monitoring to predict the next maintenance interval. RCM may be the way of the future, but at this point only a few generating sites have sufficient system capabilities and sensors installed to monitor and collect information to perform predictive diagnostics. This paper is not intended to address the various types of maintenance approaches or to promote one method over another. Many papers are available to cover the various methods. Utility generating facilities are having difficulty maintaining a knowledge base with employees due to attrition. Utilities are seeking a method of maintaining and transferring maintenance procedures and accumulated knowledge to new hires. Much of the knowledge is based on equipment manufactured between 1945 and 1978. Without a method of knowledge transfer and training, the information and proven procedures will be lost.

Manufacturer's Recommendations

Manufacturers create instruction manuals with maintenance intervals to span vast numbers and types of industries for general "standard operating conditions" as stated in published IEEE, ANSI and NEMA Standards. These standards reference a range of temperature,



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altitude and humidity. It is impractical for manufacturers to address specific levels of cleanliness or exposure to contaminants. Rapid seasonal temperature changes cause condensate to form on bus conductors and insulators. Condensate combined with contaminants causes tracking on insulation systems and rust inside operating mechanisms. Either condition or a combination of both can prevent proper operation or cause premature failure. IEEE Standard C37.12.1 provides guidance to manufacturers on what to include in instruction manuals, but does not control nor suggest any specific intervals. Most manufacturers recommend the service interval to coincide with their initial warranty period. For medium voltage (MV) power circuit breakers and busway this is typically 1-2 years. Properly applying MV power circuit breakers per IEEE Standards and performing the recommended maintenance will help extend their useful life.

Electrical Equipment Life

The textbook definition of electrical equipment life is the point at which equipment no longer performs its intended function, either mechanically or electrically. So what determines electrical life? It could be one or several of the following conditions:

- Mechanical operations
- Load (Thermal)
- Ambient temperature
- Air quality
- Service conditions
- Insulation life
- Age

When maintenance is performed at appropriate intervals and MV power circuit breakers and bus conductor systems are applied within their ratings, an operational life of 35-50 years is possible as long as renewal parts are available. Some aspects of the above listed parameters that govern electrical equipment life do not apply to bus systems, so the discussion will be limited to MV power circuit breakers unless a failure mode is pertinent to bus conductor systems.

Causes of Circuit Breaker Failure

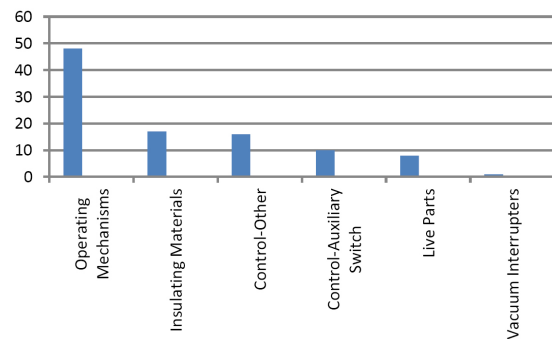
An understanding of the causes and frequency of failures of MV power circuit breakers can be used as a guide to tailor a maintenance program. Monitoring pertinent performance parameters and initiating corrective actions can usually prevent failure of MV power circuit breakers and prolong their expected life. A failure is defined as any unsatisfactory operation of a power circuit breaker or bus system. The failure of a MV power circuit breaker may be:

- Failure to trip or close properly
- Overheating
- Mechanism failure
- Insulation failure
- Failure to interrupt

The Institute of Electrical and Electronics Engineers (IEEE) continuously collects data on the failure of power circuit breakers and compiles the results in the IEEE Gold Book. The following represents a summary of failure modes. (See Table 1)

- Operating mechanisms 48%
- Insulating materials 17%
- Control-other 16%
- Control-Auxiliary Switch 10%
- Live parts 8%
- Vacuum Interrupters <0.01%

Table 1. Power Circuit Breaker Failure Modes



A review of the data indicates it is a good idea to concentrate on the maintenance of power circuit breaker mechanisms and insulation as a first step to extend their useful life.

Application Considerations

Any maintenance plan should first consider the application of the power circuit breaker. Most power circuit breakers are used to isolate and protect primary feeds to transformers and other line-ups of MV switchgear. These power circuit breakers may see less than 400 operations over a 45-50 year service life. The typical design life of most circuit breaker mechanisms is 10,000 no-load operations. The recommended service interval is 2000 operations. These intervals are based on short circuit and continuous current of each rating category. Based on these design parameters, most circuit breakers would never receive any maintenance service.

This is a dangerous approach for any application. However, some power circuit breakers are misapplied as motor starters and these applications will shorten the expected life of the breakers as well as require more maintenance. Breakers used as motor starters can experience over 1000 operations each year with magnetic inrush currents of 2-3 times the rated full load current of the power circuit breaker. High numbers of operations with magnetic inrush stresses the circuit breaker mechanism and creates increased wear in the mechanism components as well as the main contacts. A medium voltage fused contactor is a much better device for motor starting.

Ambient conditions such as temperature changes, high humidity and chemical contaminants in the air increase the formation of rust in ferrous metals. This also accelerates tracking and dielectric breakdown of insulating materials. When circuit breakers must be used in areas that are subjected to unfavorable ambient conditions, it is recommended that they be maintained on a more frequent basis to avoid unexpected failures. The general rules for electrical equipment are:

- Keep it dry
- Keep it clean
- Keep it cool
- Keep it tight

Breaker Operating Mechanisms

Operating mechanisms (OM) experience failures related to lubrication issues, mechanical wear, improper adjustments or assembly after repair or reconditioning. This is often due to a lack of specific information from the original equipment manufacturer (OEM) or failure to perform scheduled maintenance. In some cases, the OEM may no longer be in business and data is no longer available. Since breaker mechanisms are the number one cause of failure in power circuit breakers it is important to perform proper maintenance and testing on them for optimum performance. Experience has shown that mechanisms fail because the breakers see excessive operations between maintenance intervals. Conversely, the lack of operations allows the grease to harden and prevents proper opening or closing of the mechanism. Either situation can cause a catastrophic failure.

A service interval of 2-4 years is typically acceptable for power circuit breaker mechanisms that operate 6-10 times each year. This rule of thumb applies only to clean switchgear rooms with average ambient conditions and no contamination. Scheduled maintenance should include all the manufacturer's recommendations. Lubrication, cleaning and mechanism timing should never be skipped. If the grease shows any signs of hardening or the timing is slower than recommended, the mechanism should be disassembled, cleaned and re-lubricated with the manufacturer's recommended lubricant prior to reassembly. Never change or substitute lubricants without getting permission from the OEM. If no OEM data is available, substituting a synthetic-based lubricant that contains molybdenum-disulfide should never create an issue. If the mechanism is disassembled, check for signs of wear and replace all worn mechanism components with OEM parts. Never substitute components or use "reverse engineered"/counterfeit parts unless they have been design verified by testing to the appropriate IEEE Standards for the specific equipment. Always demand a copy of the design test certificate on all non-OEM parts.

Some manufacturers have test methods to determine the excess mechanism energy available during a close-and-latch operation. If the design has this capability, there is usually a method of documenting the excess energy/over-travel of the mechanism. This should be recorded and compared at each service interval to determine if the mechanism is losing energy. This is a good indicator of the need for lubrication or a major reconditioning procedure. A circuit breaker's interrupting time depends on mechanism speed and closing energy, so mechanism timing is critical to successful operation. It is far better to repair the mechanism and verify its performance before it experiences a major failure.

Insulation Systems

Insulation systems in medium voltage circuits have two states. They are either functioning or they have failed. Insulation system life is determined by several factors. One is temperature. Most insulation systems in MV switchgear have either Class A (105° C) or Class B (130° C) total temperature. For every 10° C the operating temperature of the primary conductors exceeds the temperature rating of the insulation, the insulation life will be cut in half. Prior to a total failure, there may be increased corona at attachment joints and high partial discharge may be detected. But if there is no testing or continuous monitoring of these conditions, failure may occur before it can be detected. If mechanism failures don't get you, insulation failures will. This is why many manufacturers frown on maintenance intervals that extend beyond 5-6 years regardless of the condition of a breaker's mechanism. This applies to power circuit breakers as well as bus conductor systems.

Thermographic scans help identify loose bus joints and connections if they are performed annually. The switchgear must be energized and fully loaded. MV metal-clad switchgear also has metal barriers between the horizontal main bus compartment and the cable compartment. If infrared scans of the bus are to be performed, the switchgear must be modified to include viewing windows to allow the infrared camera direct line-of-sight to the joints. This may not be practical, so a de-energized inspection may be required. Partial discharge monitoring systems will also detect corona on energized switchgear bus and can be used to trend the degradation of insulation before a total failure occurs.

Figure 1 is of a switchgear main horizontal bus system in MV switchgear. The damage may have been the result of contaminants, lack of cleaning, moisture or partial discharge due to air gaps between the bus insulation and horizontal bus bracing windows. Luckily this was discovered during a routine maintenance outage and was repaired before a major bus failure occurred. A history of the bus insulation temperature is useful data to be included in a CBM program. In fact, maintaining historical data and test records of all electrical equipment contributes to improving condition based maintenance programs.



Figure 1.

Financial Impact

Conditioned based maintenance must account for changes in operation of a facility and consider revenue loss as a consequence of maintenance outages versus equipment failure. The electrical system in a hydro generating facility can easily be equated to the human body. Low voltage power circuit breakers, motor control centers and distribution panels are very much like arms, legs and fingers. The main MV power circuit breakers are the heart and main arteries. If a finger is lost, it hurts and there will be bleeding, but the loss is minor compared to ripping out the heart or one of the main arteries.

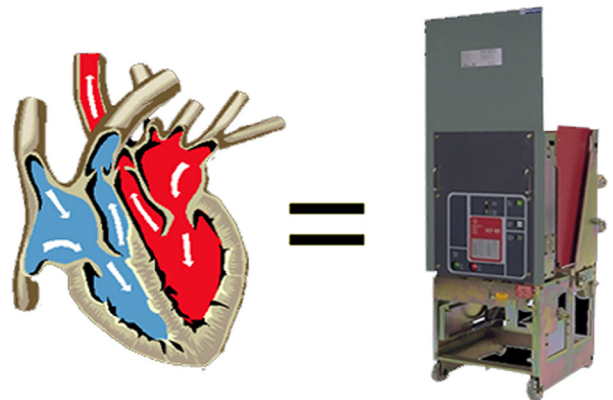


Figure 2.

Let's look at an example to quickly access the cost of not performing versus performing maintenance to a MV power circuit breaker. Assume the generating station output is 100 mega Watts and sells the power for \$.035/kwh. The plant balance of power breaker is on an A-B bus and allows selection of either source for maintenance without causing an outage of the turbine-generator. The "A" and "B" bus breakers are in the same switchgear lineup and are fed by a breaker that is physically adjacent to the "A" bus breaker. The cost of maintenance is less than \$2,000 for each of the A-B breakers and the main for a total of \$6,000, but the breakers seldom operate. The scheduled maintenance interval of two years for each breaker was not performed for eight years at a cost savings of \$24,000. An arcing fault occurs on the "A" bus breaker and the breaker fails to successfully clear the fault. The main breaker receives a trip signal, but is sluggish and also fails to clear the fault. The "A"

bus breaker causes substantial damage to the switchgear and the turbine-generator goes off line. The turbine is down for 48 hours at a revenue loss of \$168,000. This does not include the cost to repair the switchgear on an emergency basis and the future cost of a final repair.

Visual Instruction Books

We know what to look for and have an idea of what maintenance we should perform as a minimum, but how do we transfer and explain the knowledge required for the maintenance procedures. One method is to document the procedures with text, photos and video so they can be saved and transferred to future maintenance personnel. This method is called a Visual Instruction Book and contains the essential test and maintenance information. Visual instruction books, sometimes called visual instruction book essentials (VIBE), are defined as interactive graphic and video interpretations to enhance the use or testing of a product or process. VIBE is an electronic document and can be viewed at any time from most computers or tablets. VIBE is created in a portable document format (PDF). The VIBE does not replace the printed instruction book, but is used in conjunction with it to provide enhancements and clarifications that might be misinterpreted. This method also provides a way to perform interactive training using a consistent information transfer. Audio can be turned on for individual usage or turned off for instructor lead training. Visual Instruction Books:

- Illustrate things hard to visualize in print
- Provide more detail and clarification
- Use animation and video
- Initiate interaction to encourage involvement
- Are user paced

As an example, consider the need to show a specific connection of an AC hi-potential test set to perform insulation dielectric tests per IEEE C37.09 Section 5. The text from the standard requires another section of the standard, 4.4.3.1, to describe the method. It seems fairly straight forward, but can sometimes cause confusion when testing older circuit breaker designs like the GE AM13.8 that has vertical top-mounted primary conductors. An interactive diagram that is initiated by a mouse roll-over clearly identifies the test lead connections without having to research the IEEE Standards.

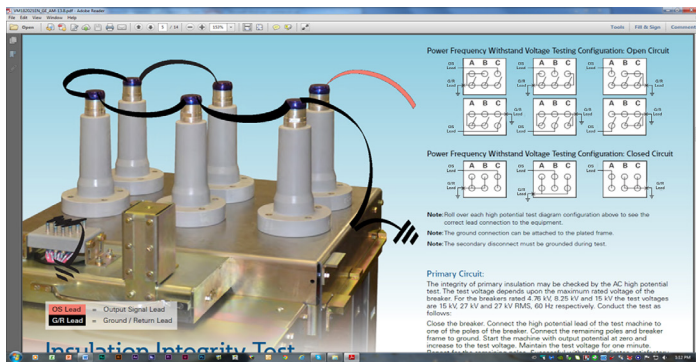
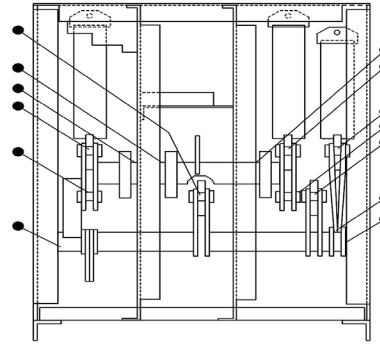


Figure 3.

Power circuit breaker mechanism lubrication can be confusing to visualize due to the number of points that require a drop of oil to “liven up” the existing lubricating grease. The addition of an auto-run video clarifies the lubrication process.



Apply one drop of light non-synthetic machine oil at each point.

Figure 4.

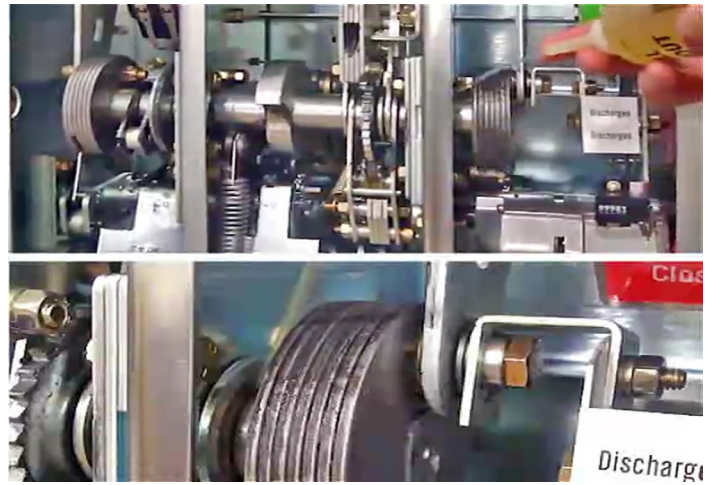


Figure 5.

Some MV power circuit breakers have the capability of having their mechanisms tested for close-and-latch energy by measuring over-travel of the mechanism shaft during a closing operation. This is usually a multi-step process and requires interpretation of the final results. The addition of an auto-run video with graphics to accompany the text and interpret the results makes the task much easier and provides training for those new to the procedure.

CloSure™ Test

Introduction: The CloSure™ Test is a simple yet intricately optimized means to determine and monitor the ability of the mechanism to close the breaker contacts fully. It provides a quantitative measure of the pulse energy available to close the breaker contacts to their full extent. If this test is used periodically to monitor the health of the mechanism.

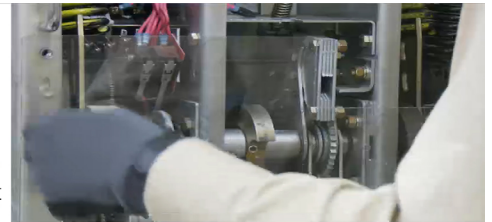
All steps, circuit breakers are called upon to operate MOC (Mechanism Operator Control) switches that close extra lead upon the closing mechanism of the circuit breaker. If this test is applied, it can prevent the circuit breaker from closing fully. In such a case, it is important to determine that the circuit breaker will close fully. The CloSure™ Test provides the assurance.

General Information: If the CloSure™ test described is to be applied, the mechanism performance is satisfactory. If the CloSure™ test does not conform as shown in the demonstration, contact Eaton for further information.

WARNING
DO NOT ATTEMPT TO REPAIR OR PERFORM MAINTENANCE OR TESTS ON THE EQUIPMENT WHILE IT IS ENERGIZED. ALWAYS WEAR YOUR SAFETY GEAR. NEVER TOUCH THE CIRCUIT BREAKER OR ITS CONTACTS OR CLOSED POSITIVE MAIN OR BUS. PERSONAL INJURY CAN OCCUR. ALWAYS VERIFY THAT NO VOLTAGE IS PRESENT BEFORE PROCEEDING WITH THE TEST AND ALWAYS FOLLOW GENERALLY ACCEPTED SAFETY PROCEDURES.

Safety Precautions: Read and understand the instructions provided for specific instructions before attempting any maintenance, repair or testing on the breaker. The user is cautioned to observe all recommendations, warnings and cautions relating to the safety of personnel and equipment. The recommendations and information contained herein are based on experience and judgment, but should not be considered to constitute an offer of any warranty, express or implied, or a representation of any kind. For further information in required, you should consult an Eaton Electrical Services and Systems representative.

Testing Procedure: Assuming that the circuit breaker is fully energized from the substation and you follow the procedure to perform the CloSure™ test. For further instructions on removal of the circuit breaker from the substation, refer to the appropriate section of the instruction manual.



Remove the CloSure™ Tool

Note: 10001 element photo.

CloSure™ Tool Showing Mounting / Testing Hole Locations (65R2C48051)

BREAKER LINE	APPROXIMATE MOUNTING HOLES	UPPER MOUNTING HOLES	LOWER MOUNTING HOLES	HAZARD PLACEMENT HOLES
T001	18	A1	C1	C1
T002	22	A1	C1	C1
T003	22	A1	C1	C1

Illustrative Testing Note (Example illustration not to scale)
CloSure™ Distance = 5 1/4" Approx.
Date / # of Breaker Operations / CloSure™ Distance
8.0" to 10"

*Note: Use the center of the marker diameter to determine "X" distance

Figure 6.

Evaluate the CloSure™ Performance

Record the date and number of operations on the tape
Measure the over travel: "X"

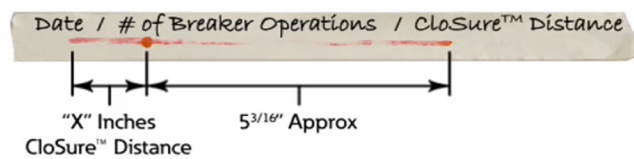


Figure 7.

Instruction books usually include a list of recommended spare parts that are the most commonly needed for repair, but seldom is a list of all the parts included with detailed drawings to assist in the part's identification. A VIBE can have an embedded 3D drawing with a drop-down bill of material (BOM) to identify most items in an assembly. An example of a 3D model with an indented BOM is included.

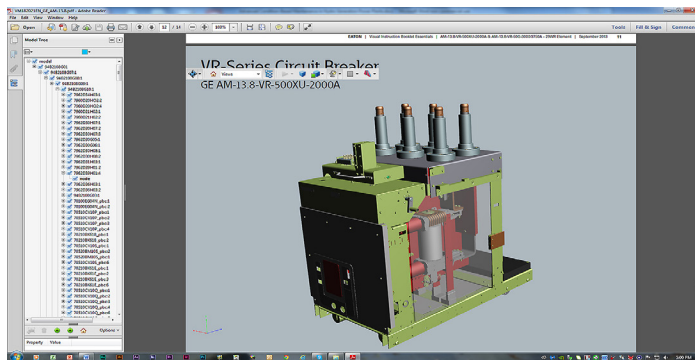


Figure 8.

A full working model of a VIBE can be downloaded at no charge from Eaton.com at the following link:

<http://www.eaton.com/VR-Series>

Go to the Multimedia tab and select the VIBE desired.

Conclusions

Electrical equipment life of MV Power Circuit Breakers and bus conductor systems can be extended well beyond initial expectations. Proper application and environmental concerns are necessary to prevent catastrophic failure due to overload. Maintenance based on manufacturers' recommendations may not be sufficient to achieve the most cost effective plan in a hydro generating facility. CBM that considers the manufacturers' recommendations, operational history, past maintenance records and operational changes will yield the most cost effective plan. Visual instruction books provide a basis for knowledge transfer and consistent training.

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