MEDIUM-VOLTAGE EQUIPMENT MONITORING AND DIAGNOSTICS: TECHNOLOGICAL MATURITY MAKES CONCEPTS COMPATIBLE WITH EXPECTATIONS

Simone TURRIN	Bernhard DECK	Marco EGMAN	Luca CAVALLI
ABB AG – Germany	ABB Sécheron S.A. - Switzerland	ABB S.p.A. – Italy	ABB S.p.A. - Italy
simone.turrin@de.abb.com	bernhard.deck@ch.abb.com	marco.egman@it.abb.com	luca.cavalli@it.abb.com

ABSTRACT

For a long time the "monitoring and diagnostics" and the closely linked "condition-based maintenance" concepts have been widely described in technical literature but finding a real, widespread, convenient application for medium-voltage (MV) breakers and switchgears in the real world has been more challenging. The difficulty of applying sensing technologies, especially in the field, the uncertainty in data interpretation and the subsequent unpredictable return on investment are challenging their promoters. Historically, condition monitoring solutions for MV breakers and switchgears focused on equipment operations (i.e. operating time, travel speed, phase synchronization, number of operations, etc.). But many important aspects are yet to be fully explored. For example, what about devices that stay closed for years without making a single operation? Is it possible to monitor them in an effective way, determine their current health condition and ensure they will open when needed? Other two very popular subjects related to condition monitoring of MV equipment are temperature monitoring of power connections and partial discharge measurements. The first subject has seen a long evolution through many technological improvements and nobody disputes now the validity of its application. On the other hand, the use of partial discharge measurements to monitor the health condition of MV breakers and switchgears is much more recent and it is becoming increasingly popular despite many experts are considering it not fully mature for delivering reliable results. What is true in this respect and what condition monitoring techniques are trustworthy based on the current state of technology? This paper reviews the most popular approaches in condition monitoring for MV breakers and switchgears and analyzes their technological maturity. Some well-known pitfalls concerning the most compatible monitoring and diagnostic solutions are highlighted. Finally, the paper presents a list of open issues and research needs on the way to the realization of widespread and convenient applications of "monitoring and diagnostics" and ""condition-based maintenance" for MV breakers and switchgears.

INTRODUCTION

Condition Based Maintenance (CBM) utilizes data collected by condition monitoring systems to estimate the current health condition of an equipment and to identify the need of maintenance activities. CBM mainly consists of the following steps: data acquisition, data processing and maintenance decision-making. The main processes involved in data processing are: data accumulation, data transmission, data storing and data analysis [1]. The efficient implementation of a CBM strategy allows the paradigm shift from preventive maintenance (with maintenance activities planned based on the equipment operational time or the number of operations, irrespectively of the actual condition of the equipment) to predictive maintenance (with maintenance activities planned based on the actual health condition of the equipment).

CBM requires monitoring critical failure modes to fulfil the following requirements:

- Identify a pending potential failure and provide recommendations for an appropriate short-term maintenance activity (diagnostics);
- Predict a future potential failure and suggest the appropriate long-term maintenance activities or mid-term equipment operational changes (prognostics).

Paoletti et al. [1] provide useful guidelines related to the parameters to be monitored for electrical equipment. These guidelines are based on a statistical review of IEEE data [2] and on a more recent end-user feedback. According to these guidelines, the parameters than can be monitored for MV breakers and switchgears in order to detect a pending potential failure are:

- Temperature;
- Partial discharge;
- Humidity and presence of water;
- Dust.

The "IEEE Guide for the Selection of Monitoring for Circuit Breakers" adopts a different approach based on failure modes and effects analysis (FMEA) [3]. According to Carlson [4], "a failure mode is the manner in which the item … potentially fails to meet … the intended function and associated requirements". The approach presented in [3, 5] can be shortly described by the following five steps:

1. FMEA to identify potential failure modes and their effects;
2. Determining monitoring options for each relevant failure mode;
3. Risk analysis;
4. Cost benefit analysis;
5. Decision making.

In the following sections of this paper, we will follow a similar approach. We will at first identify the most critical failure modes by assessing the risk related to the typical failure modes for MV equipment. Then, for the most critical failure modes, we will list the most popular monitoring options and we will review their technological maturity in terms of accuracy and cost. Finally, based on this analysis, in the last part of the paper the main open issues and research needs in monitoring and diagnostics for MV breakers and switchgears will be presented.

DETERMINATION OF MOST CRITICAL FAILURE MODES FOR MV EQUIPMENT

According to [3], authors' comprehensive knowledge of MV equipment and an internal statistical analysis of field failure data, typical failure modes for MV breakers and switchgears are:

a. Fails to open on command;
  - a.1. Opens but fails to remain open;
  - a.2. Opens but fails to interrupt;
  - a.3. Opens but fails to maintain open contact insulation;
  - a.4. Opens without command;

b. Fails to close on command;
  - b.1. Closes but fails to conduct current;
  - b.2. Closes without command;

c. Fails to conduct continuous or momentary current (while already closed);

d. Fails to provide insulation;
  - d.1. Fails to provide insulation to ground;
  - d.2. Fails to provide insulation between phases;
  - d.3. Fails to provides insulation across the interrupter – external;

e. Fails to contain insulating medium;

f. Fails to indicate condition or position;

g. Fails to provide for safety in operation.

The criticality of each failure mode can be determined by a risk assessment [3]. The risk assessment is based on the determination of a so called risk index that is composed by two factors: the probability of occurrence and the consequence in case of occurrence. Probability and consequence can be classified according to Table 1.

	Classification of probabilities	Classification of consequences
1	Improbable	Negligible
2	Infrequent	Moderate
3	Occasional	Major
4	Frequent	Catastrophic

Table 1: Classification of probabilities and consequences.

After determining the probability and consequence of a failure mode, its risk index can be assessed accordingly to the matrix reported in Table 3. Table 2 provides a description of the different risk indexes.

Description of risk indexes	
A	Highest risk, immediate action required to reduce risk
B	Major risk, not desirable, moderate action required to reduce risk
C	Moderate risk, acceptable with controls to mitigate risk
D	Minimal risk, acceptable risk without mitigating action

Table 2: Classification of risk [3].

A risk assessment is performed by the authors for the failure modes listed at the beginning of this section. The numerical values of probability (in terms of failures per year) corresponding to the 4 different categories reported in Table 1 are classified as confidential information and not for public disclosure.

Risk index		Consequence			
		1	2	3	4
Probability	1	D	D	C	B
	2	D	C	B	B
	3	C	B	A	A
	4	B	B	A	A

Table 3: Risk matrix.

It is important to note that the consequence of a failure usually does not change, once identified On the other hand, the probability of occurrence of the same failure may change (i.e. due to mitigation actions). In determining the consequence of a failure, the effects of the failure on human and environmental safety has been considered has crucial for this paper. The result of the risk assessment is reported in Figure 1.

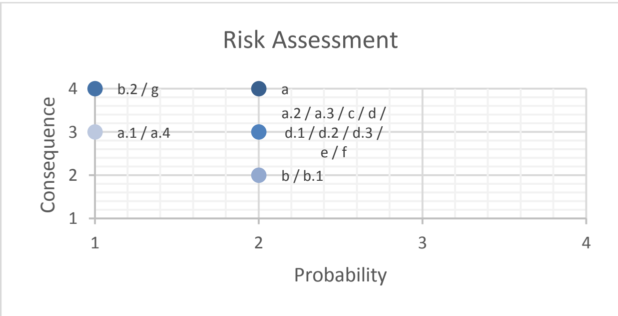

Figure 1: Risk assessment for typical failure modes related to MV breakers and switchgears.

As illustrated in Figure 1, all failure modes are characterized by a low probability of occurrence (from improbable to infrequent) but by dramatic consequences in case of failure. No failure mode is associated to the highest risk index (in that case a re-design of the equipment would be suggested in order to reduce the probability and/or the consequence of the failure). In the following, we will focus only on the most critical failure modes, which are the failure modes associated to a major risk (i.e. risk level equal to B in Table 4). These failure modes are:

- Fails to open on command (a, a.2, a.3)
- Fails to close on command - Closes without command (b.2)
- Fails to provide insulation (d, d.1, d.2, d.3)
- Fails to contain insulating medium (e)
- Fails to indicate condition or position (f)
- Fails to provide for safety operation (g)

The failure mode "Fails to conduct continuous or momentary current (while already closed)" (c) is not considered here, since the risk of such a failure mode is between moderate and major.

FAILURE MODES, MONITORING OPTIONS AND THEIR TECHNOLOGY MATURITY

Based on [3], authors' extensive knowledge and experience of MV equipment and a comprehensive literature research, the most significant monitoring options for each critical failure mode (i.e. failures modes associated to a major risk) are reported in this section. The focus is on indoor vacuum circuit breakers, even if some aspects related to outdoor installations and gas insulated circuit breakers are considered as well. Additional details on the failure effects related to each failure mode are reported in [3]. The technology maturity of each monitoring options is expressed in terms of accuracy and cost. With the term "accuracy", the accuracy in detecting and measuring the physical variables of interest as well as the accuracy in analyzing and interpreting the measurements for diagnostics is meant. With the term "cost", the cost of the monitoring system (i.e. mainly sensors and processing unit) as well as eventual downtime costs (in the case that monitoring cannot be performed for an energized equipment) is meant. The accuracy and cost are classified in high, medium and low respectively. The list of monitoring options reported in this section is not exhaustive but considers the state of the art in monitoring and diagnostics for MV equipment and current internal and external research projects.

Fails to open on command (a, a.2, a.3)

Fails to open on command (a)			
Failure cause	**Monitoring option**	**Technology maturity**	
		Accuracy	**Cost**
Open or shorted trip coil	Monitor trip coil continuity or impedance	High	Low
Inappropriate or inadequate lubrication	Monitor trip coil energy consumed	Medium	Medium
	Monitor current and voltage drop during time for circuit breaker to operate	Medium	Medium to high
	Monitor time for the circuit breaker to operate	Low	Low
Loss of stored interrupting energy	Monitor position of store energy springs	Low	Low
Mechanical failure	Monitoring nr. of operations	Low	Low
	Monitor operating time	Low	Low
	Monitor primary current interruption during change of state operating mechanism	Low	Medium
	Monitoring vibrations	Medium	Medium
	Monitoring electrical variables for spring charging motor	Medium	Low

Table 4: Monitoring options and their technology maturity for the failure mode "Fails to open on command (a)"

In monitoring the failure mode "Fails to open on command", the accuracy in assessing the health condition of the operating mechanism is one major issue. Despite the relative simplicity in monitoring mechanical (vibrations, forces, etc.) and electrical (current, voltage, etc.) variables, a reliable algorithm assessing the condition of the operating mechanism based on the monitored variables is still a research topic. This is mainly due to the complexity of the mechanism and on the variety of sub-components that may fail. Another issue is given by monitoring breakers that are closed for years without making a single operation. In this case, a dedicated monitored technology is still missing.

Fails to open on command – Opens but fails to interrupt (a.2)			
Failure cause	**Monitoring option**	**Technology maturity**	
		Accuracy	**Cost**
Loss of vacuum	Periodic vacuum integrity overpotential test	High	High
Low gas pressure or density (air or SF_6)	Monitor gas pressure or density	Medium	Medium
	Monitor gas pressure or density together with the ambient temperature	High	Medium
Arc chute failure	Monitor temperature	Low	Medium
	Monitor partial discharge	Low	Medium
Mechanical failure	Monitor mechanism position and auxiliary contacts with respect to current flow and opening signal	Medium	Low
Contact ablation	Monitor peak of interrupted current	Medium	Low
	Monitor time-resolved current	Medium	Medium
	Monitor contact pressure	Low	Medium
	Monitor contact temperature	Medium	Medium
	Monitor contact resistance	High	High
	Monitor acoustic emission	Medium	Medium

Table 5: Monitoring options and their technology maturity for the failure mode "Fails to open on command - Opens but fails to interrupt (a.2)".

Monitoring the contact ablation is a topic that received a lot of attention in the last years. The accuracy in assessing contact wear is quite satisfactory but, due to the criticality of this failure mode, improvements are still currently investigated (one research direction is given by adapting costly HV technologies to MV equipment).

Fails to open on command – Opens but fails to maintain open contact insulation (a.3)			
Failure cause	**Monitoring option**	**Technology maturity**	
		Accuracy	**Cost**
Loss of vacuum	See Table 6		
Low gas pressure or density (air or SF_6)	See Table 6		
Mechanism does not travel complete distance	Monitor mechanism position	Medium	Low
Too many operations in a time period	Monitor number of operations over time period	Low	Low

Table 6: Monitoring options and their technology maturity for the failure mode "Fails to open on command - Opens but fails to maintain open contact insulation (a.3)".

Closes without command (b.2)

Fails to close on command – Closes without command (b.2)			
Failure cause	**Monitoring option**	**Technology maturity**	
		Accuracy	**Cost**
Stray current in close circuit	Monitor current in close coil	Medium	Medium
Unwanted power on intertrip signaling	Supervising energy level of remote input signals	Medium to high	Medium
Spring release mechanism worn	Monitor movement of release mechanism	Low	Medium
	Monitor vibrations	Low	Medium

Table 7: Monitoring options and their technology maturity for the failure mode "Fails to close on command - Closes without command (b.2)".

Fails to provide insulation (d, d.1, d.2, d.3)

Fails to provide insulation (d)			
Failure cause	**Monitoring option**	**Technology maturity**	
		Accuracy	**Cost**
Loss of vacuum	See Table 6		
Low gas pressure or density (air or SF_6)	See Table 6		
Wear-generated particles in interrupter	Monitor partial discharge	Low	Medium
	Monitor dirt and pollution	Medium	High

Fails to provide insulation to ground (d.1)			
Excessive temperature of insulating materials	Monitor ambient air or component temperature	Low	Low
Fails to provide insulation between phases (d.2)			
Ionization of surrounding insulating air	Monitor partial discharge	Low	Medium
Water infiltration	Monitor partial discharge	Low	Medium
	Monitor humidity and presence of water	Low	Low
Fails to provide insulation across interrupter – external (d.3)			
Water infiltration	See above		
Dirt or pollution	Monitor dirt and pollution	Medium	High
Ionization of surrounding insulating air	See above		
Deterioration of interrupter exterior surfaces caused by partial discharge	Monitor partial discharge	Low	Medium

Table 8: Monitoring options and their technology maturity for the failure mode "Fails to provide insulation (d)" and the subsets "Fails to provide insulation to ground (d.1)", "Fails to provide insulation between phases (d.2)" and "Fails to provide insulation across interrupter – external (d.3)".

Several research activities have been conducted in the past on monitoring partial discharges. Despite the availability of relatively cheap and accurate technologies to detect partial discharges, the authors' opinion is that some work is still necessary in developing reliable data analytics able to relate the detected partial discharges to a potential pending failure (and the corresponding affected components).

Fails to contain insulating medium (e)

Fails to contain insulating medium (e)			
Failure cause	**Monitoring option**	**Technology maturity**	
		Accuracy	**Cost**
Loss of vacuum	See Table 6		
Low gas pressure or density (air or SF_6)	See Table 6		

Table 9: Monitoring options and their technology maturity for the failure mode "Fails to contain insulating medium (d)".

Fails to indicate condition or position (f)

Fails to indicate condition or position (f)			
Failure cause	**Monitoring option**	**Technology maturity**	
		Accuracy	**Cost**
Defective closed, opened, or stored energy	Monitor indication with signal to open and close circuit,	High	Medium

indicator	etc.		

Table 10: Monitoring options and their technology maturity for the failure mode "Fails to indicate condition or position (d)".

Fails to provide for safety in operation (g)

Fails to indicate condition or position (g)			
Failure cause	**Monitoring option**	**Technology maturity**	
		Accuracy	**Cost**
Overpressure of pneumatic or hydraulic fluids, spring charging system	Monitor gas pressure	See Table 6	
	Monitor position of store energy springs	See Table 5	
Loss of gas and need to isolate	Monitor gas pressure	See Table 6	

Table 11: Monitoring options and their technology maturity for the failure mode "Fails to provide for safety in operation (g)".

OPEN ISSUES AND RESEARCH NEEDS

An overview of the current situation regarding technology maturity of condition monitoring for MV equipment, referred to the most critical failure modes, is reported in Figure 2. Based on Figure 2 and the results of the previous section, a satisfactory accuracy at an acceptable cost is currently available to efficiently monitor the majority of critical failure modes for MV equipment. Nevertheless, research activities are still needed to increase the accuracy of monitoring the operating mechanism and the equipment insulation. Despite accurate and relative cheap measurement and detection of the relevant physical variables (e.g. vibrations, partial discharges), the issue here is the development of a reliable analytics that relates the monitored variables to a credible estimation of the equipment condition. This is due, for example, in the case of partial discharge measurements by the difficult interpretation of the measured data, from either HF radiation, noise, frequency detection, etc.. Even if the measured values are accurate, the interpretation and the conclusions based on them can be still inaccurate and unreliable. The increasing availability of monitoring data as well as advances in data mining and statistical methods may contribute to the solution of this issue.

Finally, the intimate integration of sensors in the new generation of circuit breakers for using them either in new switchgear or as main portion of retrofitting equipment looks very promising. This thanks to the ease of integration in MV devices, the higher and higher accuracy they can reach, and the accessible cost at which they can be provided. All these aspects are very much strengthened by the avoidance of the site works for the system upgrade.

Three main areas of sensors applications can be identified:

- Mechanical endurance monitoring of the cinematic chain from the operating mechanism to the poles, detecting speed, torsion, pressure, bouncing and vibrations.
- Temperature monitoring of the circuits embedded into the power interfaces.
- Environmental data monitoring like humidity, pollution, ozone concentration and noise in a single multipurpose chip.

The integration of a reliable partial discharge measuring system onboard MV breakers seems at the moment challenging because of the difficult balance of efforts, costs and results.

CONCLUSION

This paper focuses on the analysis of the technology maturity of MV equipment monitoring. After identifying the most critical failure modes and the corresponding available monitoring options, the authors offer a qualitative assessment of the accuracy and cost related to the most popular monitoring technologies. The technology maturity of monitoring options for the majority of the critical failure modes makes concepts compatible with the expectations related to monitoring and diagnostics and, consequently, to CBM. Nevertheless, in authors' opinion, research is still necessary to improve the accuracy of monitoring the operating mechanism and the insulation of the equipment.

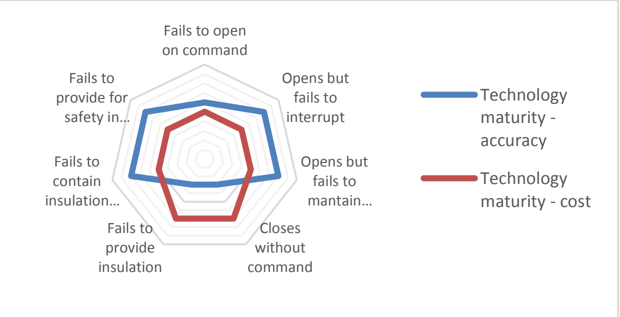

Figure 2. Summary of technology maturity (in terms of accuracy and cost) for the most relevant failure modes.

REFERENCES

[1] G.J. Paoletti, and G. Herman, 2013, "Monitoring of electrical equipment failure indicators and zero-planned outages: past, present and future maintenance practices", *Proceedings of Petroleum and Chemical Industry Technical Conference (PCIC)*, IEEE, 1-9.

[2] IEEE Standard 493-1997, 1997, *IEEE Recommended Practice for Design of Reliable Industrial and Commercial Power Systems – Gold Book*, IEEE Inc, New York, USA.

[3] IEEE Standard C37.10.1-2000, 2000, IEEE Guide for the Selection of Monitoring for Circuit Breakers, IEEE Inc., New York, USA.

[4] C.S. Carlson, 2012, *Effective FMEAs*, John Wiley and Sons, Inc., Hoboken, USA.

[5] C. Sweetser, W.J. Bergman, et al., 2002, "Strategies for selecting monitoring of circuit breakers", *IEEE Transactions on Power Delivery*, vol. 17, no. 3, 742-746.