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NON-INTRUSIVE METHODS FOR CONDITION ASSESSMENT OF DISTRIBUTION AND TRANSMISSION SWITCHGEAR

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NON-INTRUSIVE METHODS FOR CONDITION ASSESSMENT OF DISTRIBUTION AND TRANSMISSION SWITCHGEAR

JWG A3.32/CIRED

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EXECUTIVE SUMMARY

Over the last decade, the plummeting prices for renewable and energy storage, coal power in decline, the proliferation of distributed energy resources, and grid modernization with the subsequent two-way power flow, have meant that power transmission and distribution are going through rapid changes.

Not only is the power system changing, switchgear design is following suit. To adapt to the need of the modern electrical system, we have witnessed the evolution from a manual operated switch to an interconnected "smart" switch with embedded sensors, digital protection and control devices. New switchgear standards have been developed, resulting in safer, more environmentally friendly devices. With the development of novel materials and design concepts, switch sizes have reduced. All of this has resulted in increased switchgear functionality and connectivity.

At the same time, requirements for the electrical grid are becoming more stringent; including reduction of power outages, higher safety, health and environmental requirements, and better power quality. Such requirements have a large impact on the switchgear specifications and design.

In the aim to optimize the maintenance costs of switchgear equipment, there is a general trend in the utilities to move from systematic, time-based, maintenance to condition based and risk based maintenance by taking advantage of modern diagnostic tools and the advancing transformation of the network to the smart grid. There are many diagnostic techniques available today for the condition assessment of switchgear equipment.

This technical brochure provides a comprehensive information on Non-Intrusive Condition assessment of the T&D switchgear, that can be applied on HV and MV circuit breakers, HV and MV switches, MV reclosers and fault interrupters.

In order to clarify the process of condition monitoring, some terms are defined. Non-Intrusive Condition assessment methods are defined according to a following scale.

- Non-intrusive: The switchgear is not affected.
- Minimally intrusive: No major tests or repairs required before returning to service.
- Intrusive: Tests are necessary before returning to service

The intrusiveness is considered for both the switchgear and the grid, and during installation and during operation. The usefulness of the condition assessment method and the degree of maturity are also defined.

A total of 53 condition assessment methods for switchgear are presented. Examples include: electromagnetic transient emission measurement, partial discharges detection, dynamic resistance measurement, online temperature monitoring, vibrations measurement, gas leaks detection, vacuum integrity inside VI, and analysis of gas decomposition products. The majority of them can be used for both MV and HV switchgear.

The discussed methods are classified in three different categories according to the part of the switchgear that is measured: primary path (contacts, switching and isolation), mechanical parts (both mechanical linkage and driving mechanism), and control and auxiliary circuits. Each method is described in detail with the application, the theoretical background, and the ease of use and the constraints. Many of the methods are very mature and some are still in investigation phase.

The usage of non-intrusive diagnostics is covered by two means: an international survey conducted by the JWG that included questions about the methods and experience with condition monitoring, and a selection of recent case studies the authors found in the literature. The case studies show how different methods are applied. In some cases non-intrusive diagnostics allowed to avoid major failures by detecting on time a malfunction or a beginning of degradation based on the actual condition of the switchgear.

The technical and economic benefits of non-intrusive condition assessment methods must be weighted taking into account its implementation and other associated costs, installation versus the costs generated by the possible failures the equipment might encounter between maintenance periods. Several failure modes are presented for a live tank high voltage circuit breaker. Three main cost elements have been identified: investment in the non-intrusive method, maintenance costs with and without the non-intrusive method and failure/outage costs with and without the non-intrusive method. The cost calculation contains several values that should be estimated by the user.

Lastly, some trends of the development of condition-monitoring methods for circuit breakers are summarised, for example monitoring of new isolation gases and further development of partial discharge diagnostics.

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1. INTRODUCTION

Condition assessment (CA) is the process of monitoring a parameter or condition indication in machinery (vibration, temperature etc.), in order to identify a significant change which is indicative of a developing fault. It is a major component of predictive maintenance. The use of CA allows maintenance to be scheduled, or other actions to be taken to prevent failure and avoid its consequences.

In the past, two CIGRÉ working groups analyzed issues related to CA of high voltage (HV) equipment: 13.09 and B3.12. No work has been done by CIGRE for CA in medium voltage (MV) equipment. And, thus far, no CIGRE work has been done specifically on Non-Intrusive Condition Assessment Methods (NICAM).

- TB 167 (WG 13.09) [CIGRE_167_2000] gives a general overview on the philosophy and application of CA to HV switchgear. It does not focus on the analysis of the monitoring methods. This work îs used as a reference [CIGRE_167_200] for A3.32 but the new focus is in the detailed review of the state of the art technology and future trends on specifically non-intrusive methods.
- The TB 462 (WG B3.12) [CIGRE_462_2011] treats the issues related to on-line CA in HV substations. The main conclusion is that information obtained from CA can provide the relevant value for asset life management; the economic effectiveness however is not straightforward but can be demonstrated on the basis of probabilistic calculations.

CIGRE/CIRED A3.32 JWG was approved in late 2013 and tasked to review the current and future trends of non-intrusive, especially in service, diagnostic methods to apply in the CA of HV and MV Circuit breakers, reclosers and fault interrupters. In addition, it was tasked to provide feed-back and experience from utilities, manufacturers and service providers. The following scope of work was included in the terms of references (TOR).

- To review existing state of the art of non-intrusive methods and their field experience applied in HV and MV circuit breakers (CB), reclosers (R) and fault interrupters (FI) to assist in the evaluation of transmission & distribution equipment conditions using the different parameters such as:
    - Insulation: gas characteristics (decomposition product, pressure, etc.) and partial discharges
    - Switching: operation time, pole discrepancy, re-strike, dielectric stress assessment, arcing time and contact wear
    - Current carrying: contact resistance, temperature and position
    - Operating mechanism: number of operations, energy, vibrations and damping
    - Control and accessories: supply voltage, coil current, auxiliary switch
- To provide users experiences, case studies and application feed-back
- To analyze technical vs economical benefit for applying non-intrusive methods on CB/R/FI
- To identify future trends in the technology and switchgear user requirements

A team of 33 experts from 16 countries, representing manufacturers, academic and research institutions, and utilities was assembled and had a kickoff meeting in December 2013. Over the course of the next 3 years, the team had 11 face to face meetings, reviewed more than 200 references, conducted the utility survey and collected a number of case studies on non-intrusive switchgear condition assessment.

Also, A3.32 JWG took into account past works by working groups 13.09 and B3.12 as well as relevant ongoing activities performed by other study committees; especially by B3, for general substation live concept, by B5 for use of protection and automation enhanced infrastructure and on-line information for improvement of maintenance of CB/R/FI, and finally by D1, for development of new sensors as well as new diagnostic and analyzing methods.

This technical report is the result of that work.

In Chapter 2, the definitions and methodology for data analysis are provided. The term non-intrusive is defined and different categories of non-intrusive methods are listed.

In Chapter 3, all the non-intrusive methods are listed and divided in different groups by categorizing their characteristics. All methods are categorized by their degree of intrusion in the switchgear (non-intrusive, minimally intrusive, intrusive), condition of the switchgear while the method is used (in-service, off-service), degree of maturity (from theoretical concept to standard practice in the field), and mode of application (periodic measurement, continous measurement). In addition, each method is briefly explained, and its benefits and limitations are provided.

Chapter 4 has two parts. In the first part it provides the results from the utility survey. The survey was developed using a specialized web tool and sent to hundreds of utilities around the globe and received results from 45 respondents. The results give some insight on the current condition assessment practices from those utilities. In the second part, some of the current practices are covered in more detail.

Chapter 5 covers the technical and economic evaluation of non-intrusive CA methods. Benefits of the CA has to be weighted with its cost of installation and operation and risk of failure, yet, it might not be easy to quantify the costs and risks. This chapter give some state of the art methodologies and examples how to make a good business case for CA.

Lastly, in Chapter 6 some new developments and technology trends are mentioned that are relevant to CA; from the development of smaller and cheaper sensors to augmented reality.

2. METHODOLOGY OF ANALYSIS

2.1 INTRODUCTION

For the purpose of this brochure, this section reviews the relevant definitions and terminology. To ensure consistency with preceding publications regarding circuit breaker diagnostics, we refer to the previous definitions and outline discrepancies, especially if different meanings are given for similar expressions.

In this chapter we also provide a detailed discussion of more specifc terms such as non-intrusive diagnostic method, usefulness of the diagnostic method and the maturity level. Specific terms and abbreviation definitions are provided in APPENDIX A.

2.2 OVERVIEW OF TERMS

CIGRE WG B3.12 introduced a term of diagnosis of electrical equipment as decision aid tool for maintenance (postponing or advancing preventive maintenance, troubleshooting), residual life evaluation (prognosis, can we rely on equipment), actual performance evaluation (achieving optimum, increasing or reducing), forensic investigations, etc. The diagnosis integrates diagnostic tests and other available data to provide information on equipment condition or failure mode.

The diagnostic methods – also referred to as condition assessment methods – include technology or techniques using tests, condition measurements and other examinations that obtain one or more condition indicators or symptoms. Sensors, acquisition systems, communication, signal processing, data analysis, software and firmware would be used in the diagnostic method. Condition indicators are quantitative or qualitative values (parameters) related to the condition of one part or one function of the switchgear.

The terms condition of switchgear, diagnostic method, and diagnosis arrange themselves into the threefold relationship represented in Figure 2-1.

Figure 2-1: Threefold relationship between the switchgear, diagnostic method and diagnoses

The distinction is made in Figure 2-1 between measured physical parameters and condition indicators. Indeed, each diagnostic method uses in practice some measurements of physical parameters related to the switchgear, called condition measurements [Westerlund2014], and issues the condition indicators which are used in determining the diagnosis.

The condition measurements can have different forms and complexity, and can be acquired directly on the switchgear or elsewhere (i.e. grid current or voltage). They can be taken with already installed equipment or portable equipment. The measurements are in direct relation with the intrusive level of the method.

Figure 2-2 represents the measured physical parameter applied in switchgear condition measurements. In this figure, the primary circuit represents the HV/MV conductors and switchgear terminals as well as the bushings in the case of a dead-tank design. Some designs have the interrupter chamber embedded into a tank filled with an insulation medium. i.e. dead tank or gas insulated switchgear (GIS). For such cases the physical parameters of the tank are measured as well. Controls and auxiliary circuits include the protective relays and digital fault recorders (DFR) and any other measurements taken outside of the switchgear.

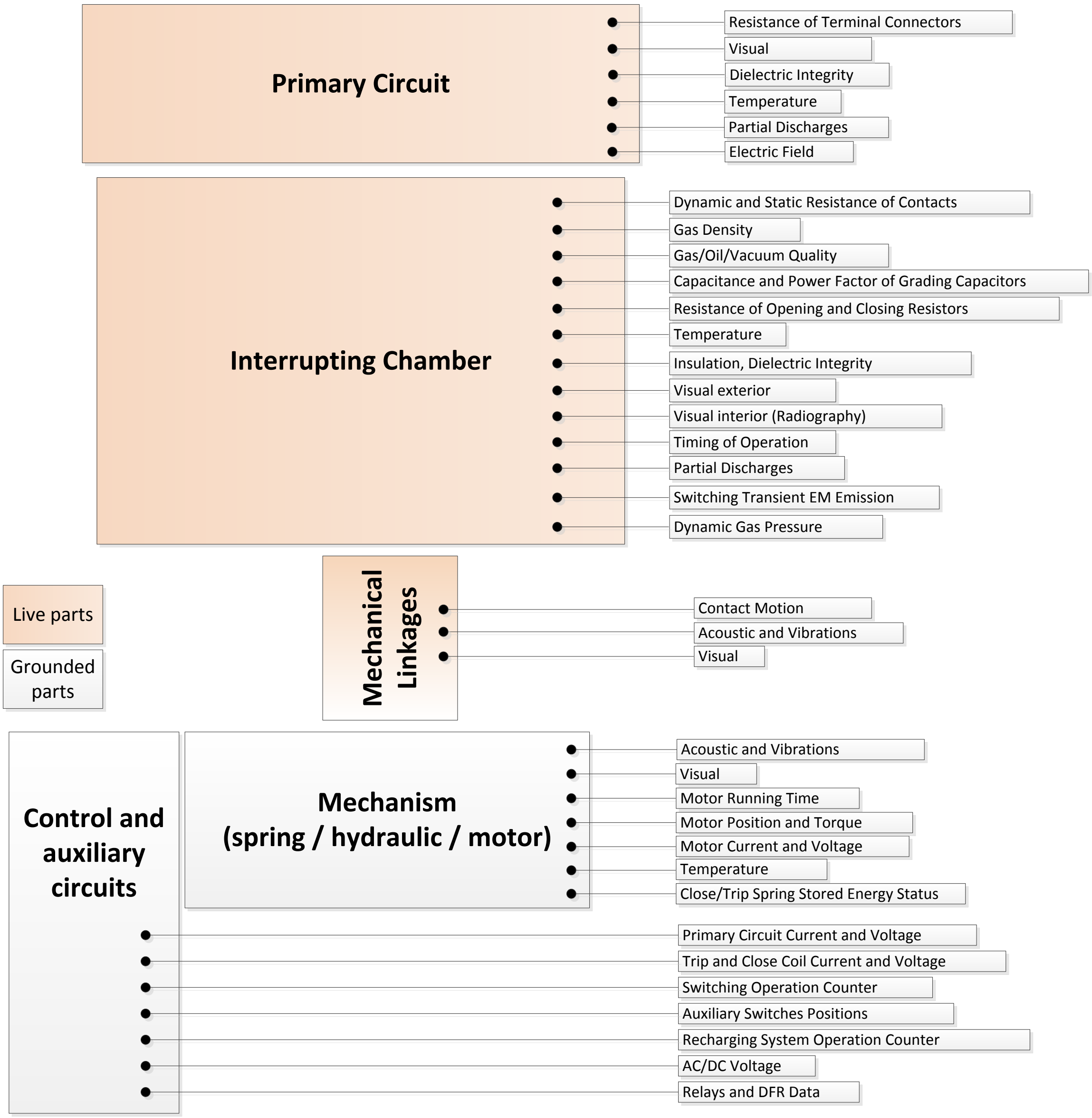


Figure 2-2: Measured physical parameters in switchgear condition evaluation

The condition indicators issued by the diagnostic methods represent the values related to the condition of the switchgear. The condition indicators can combine many condition measurements and other information. In contrast to measured physical parameters (condition measurements), which can involve a specialized interpretation, the condition indicators are straightforwardly used for diagnosis. Each section in chapter 3 describing diagnostic methods explains the required measurement and resulting condition indicators.

There is no explicit relationship between condition indicators and the diagnosis expressed in terms of standards, guides or recommended practices. The diagnosis and resulting decisions in every situation require knowing the particular thresholds, reference values, interpretation guides, etc. The following CIGRE brochures [CIGRE_167_2000, CIGRE_462_2011] and IEEE Guides [IEEE2000, IEEE2011] (see Table 5-1) introduce some guidelines on how to interpret the condition indicators in order to assess a circuit breaker condition. JWG A3.32 did not take up this challenge and concentrated on diagnostics methods and related technologies.

2.3 MEANING OF NON-INTRUSIVE DIAGNOSTIC METHOD

The adjectives intrusive/nonintrusive/non-intrusive and invasive/noninvasive/non-invasive are commonly used in technical literature complementing nouns such as diagnosis, procedure, method, technique, and etc. For instance, research of titles in IEEEXplore Digital Library shows more than 3000 documents with these terms. The spelling with hyphen after the prefix "non" seems to be privileged.

The term "non-invasive diagnostic" is precisely defined in medicine as a procedure that does not require the insertion of instruments through the skin or into a body cavity. However, following such a formal definition some simple tests, for example a venipuncture, are classified as invasive. The notion "minimally invasive" procedures were therefore introduced in medicine. In the domain of electricity, the International Electrotechnical Vocabulary (IEC 60050) defines in §212-18-35 "non-invasive testing" as testing which maintains the physical and chemical integrity of the material under test.

The difference between the terms non-intrusive and non-invasive is slight and these terms are often used as synonyms. WG A3.32 recommends using **non-intrusive** in the context of electrical equipment. It refers to the fact that there is no intrusion into the system.

There are two criteria to classify a diagnostic method of switchgear as non-intrusive: how the integrity of the switchgear itself is affected by the diagnostics and the impact on the grid.

There is no clear, and broad, definition for switchgear integrity. It should take into account the particularities of each equipment and diagnostic method. In general terms, one can suppose that the switchgear's integrity is not affected if its performance is not altered i.e., it can continue to operate within the manufacturer assigned ratings. This should be validated by relevant tests, including electrical, dielectric, mechanical and environmental performance tests, personal safety tests, life expectation, influence on adjacent equipment (i.e. EMC), etc.

The impact on the grid relates to the continued ability of the switchgear to pursue its duty during the diagnostic procedure. In this brochure, the diagnostic method is qualified as 'in-service' if the switchgear is fully functional during the diagnostic procedure and as 'off-service' if the switchgear needs to be off-duty during the procedure. WG A3.32 proposes to introduce these qualifiers in the context of switchgear diagnostics.

Consequently, non-intrusive diagnostic methods are classified as:

1. **in-service** – applied while the switchgear remains connected to the grid and can operate normally (can perform the expected duty), consequently the normal grid operation is not affected; however, in some cases the switchgear should be exercised (i.e. forced to operate)
2. **off-service** – installed or applied when switchgear is temporarily disconnected from the grid but **not affecting the integrity of the switchgear**, it can be returned to the grid after the diagnostics without any further verifications

Other methods should be classified as **minimally intrusive** or **intrusive**.

For some diagnostic methods, especially those which are installed for permanent monitoring, the distinction is required between the installation and the operation of condition measurement equipment.

If the switchgear comes with a monitoring system or some sensors installed in the factory we consider it as an intrinsic, built-in system. The switchgear integrity including this system is guaranteed by the switchgear manufacturer. Properly using such a system will be non-intrusive and eventually in-service. If a built-in factory monitoring system or sensors are optional, i.e. may not be installed before commissioning but the supports or orifices are preinstalled in the factory, then installing such a system after commissioning will be considered as non-intrusive as long as one follows the procedures provided by the factory. In these cases the manufacturer takes responsibility for guaranteeing the integrity of switchgear.

For example, removal of a cover may be considered non-intrusive (usually off-service), if the equipment can be returned to its normal duty after inspection and if it is not forbidden in the equipment manual.

If a diagnostic method involves some minor intervention or intervention limited to auxiliary subsystems and no major test or repairs to the switchgear are required after the diagnostic test, it is considered as minimally intrusive.

If a diagnostic method involves major intervention or intervention on vital parts of the switchgear, it is considered as intrusive. In this case, tests or studies are required before the switchgear is returned to service. A method requiring the switchgear to be dismantled is classified as intrusive. Usually switchgear will be examined and eventually repaired at this time and such intervention is not only an act of diagnostic but rather an ultimate act of overhaul/maintenance.

Table 2-1 below gives an overview of discussed categories.

Table 2-1 Review of categories of non-intrusive diagnostic method

Impact on grid		**Impact on switchgear integrity**	
Installation of condition measurement	operation of condition measurement	installation of condition measurement	operation of condition measurement
in-service	in-service	non-intrusive	non-intrusive
off-service	in-service	non-intrusive	non-intrusive
off-service	off-service	non-intrusive	non-intrusive
off-service	in-service	minimally intrusive / intrusive	non-intrusive
off-service	off-service	minimally intrusive / intrusive	non-intrusive
off-service	off-service	minimally intrusive / intrusive	minimally intrusive / intrusive

2.3.1 Examples of Non-Intrusive Diagnostic Method

An example of a non-intrusive method used in-service is diagnostic by measuring the transient electromagnetic emissions (TEE). The RF antennas are deployed in the vicinity of the CB and TEE are captured during a normal operation of the CB and then analyzed with specialized algorithms (section 3.3.10). Another example of non-intrusive methods used in-service is the analysis of recordings from digital relays or fault recorders. In this case, the grid is affected only during the installation of measuring equipment (such as current transformers, voltage transformers and recorders) which is usually installed when the substation is built (section 3.3.3).

An example of a non-intrusive method but used off-service is conventional timing of CB operation. The CB is disconnected from the grid and de-energized. Instruments are connected to its terminals and a few mechanical operations are performed. The CB can then be returned to its normal operation (section 3.3.12).

Some diagnostic methods are used when the switchgear is in-service but the installation of diagnostic devices requires its removal from the grid for a non-intrusive intervention. An example of such a method is a vibration analysis of the operating mechanism. In order to install the accelerometers on the walls or fixed parts in an operating mechanism compartment, the CB has to be disconnected from the grid for security purposes. This method could be classified as non-intrusive used in-service but installed off-service (section 3.3.14).

An example of the minimally intrusive method is the use of motion sensors on the CB operating mechanisms. In this case, the integrity of the mechanism may be affected because the sensor is an extra part added to the system which may influence moving parts. Moreover, there is a certain risk that the manipulations themselves may affect the integrity of the operating mechanism. Some tests or analyses are required to ensure that the performance of the operating mechanism is not altered (mass, inertia, fixations, etc.). However, one agrees that the integrity of a CB as a whole will not be affected. Its electrical performance will remain the same as long as the operating mechanism works well. No additional tests are required for switching performance (section 3.3.18).

2.4 DEGREE OF MATURITY OF DIAGNOSTIC METHOD

JWG A3.32 analyzed numerous methods described in the literature which show different degrees of maturity ranging from theoretical concept and prototypes at laboratory stage to proven products and methods with considerable experience in the field. In order to provide some guidelines in comparing the methods, two types of ratings for degree of maturity are proposed:

- simplified rating with three categories:
  - investigation
  - pilots runs
  - product available
- detailed rating with seven categories:
  - theoretical concept
  - R&D-activity
  - prototype available
  - tested in the field
  - mature product available
  - commercial product available
  - standard practice in the field

The correspondence between the categories of each type of rating is provided in Table 2-2. The simplified rating was used for the survey. The detailed rating is used for assessment of each method's maturity in chapter 3.

The detailed rating emphasizes the end-user point of view with three categories for relatively mature products and with reduced number of categories for the methods in development. For this reason JWG A3.32 did not use the universal Technology Readiness Level (TRL) scale used by many organizations including U.S. Department of Energy [DOE2011]. This nine levels scale emphasizes the development stage. The highest TRL "*Actual system operated over the full range of expected mission conditions*" assumes that the specifications are well known and the product is qualified. In the domain of switchgear diagnostics, the specifications are vague and the maturity of technology is judged rather by actual field experience than compliance to standards or guides.

The level "theoretical concept" applies to the methods which are conceptually investigated in research. The level "R&D-Activity" includes the methods having its application formulated and technology demonstrated by some experience. The level "prototype available" designates the methods where completely functional prototypes are available. If prototypes are available and some study cases are reported, than the method is rated "tested in the field". "Mature product available" is associated to the methods with significant return of field experience (many study cases) and established technology. The level "commercial product available" applies for the method where equipment or service is commercially available. Finally, "standard practice in the field" is reserved for the methods which are widely used in industry. The word "standard" does not imply that some formal standards from international organizations are available; it refers rather to *de facto* standards.

Table 2-2 Review of categories of maturity of diagnostic method

Simplified rating	Detailed rating	Symbol
Investigation	Theoretical Concept	■□□□□□□
	R&D Activity	■■□□□□□
Pilots runs	Prototype available	■■■□□□□
	Tested in the field	■■■■□□□
Standard practice in the field	Mature product available	■■■■■□□
	Commercial product available	■■■■■■□
	Standard practice in the field	■■■■■■■

The maturity levels form an ordered set except for the levels “mature product available” and “commercial product available” which are not in direct relationship. Commercially available does not mean that the product is mature and vice versa there are mature technologies never commercialized.

2.5 MODES OF APPLICATION OF SWITCHGEAR DIAGNOSTIC METHODS

Non-intrusive diagnostic methods can be classified as using periodic measurements or continuous monitoring.

Periodic measurements of the physical parameters are usually acquired with portable equipment typically during scheduled maintenance. The maintenance schedule depends either on elapsed time or on a critical number of switchgear operations. This class of diagnostic methods is particularly used when measurements have to occur during opening and closing operation. Instead of waiting for an operation to occur, closing and opening are initiated locally in order to perform measurements. These diagnostics methods are often performed off-service (such as the timing of main contacts - see section 3.3.12.1) however sometimes periodic measurements can also be performed in-service (such as transient electromagnetic emissions - see section 3.3.10).

Continuous monitoring assumes that the physical parameters are measured continuously, using permanently installed equipment. Monitoring using substation intelligent electronics devices (see section 3.3.3) and gas density monitoring using a pressure transducer (see section 3.3.4.1) are examples of diagnostic methods using continuous monitoring. They are particularly suitable for trend analysis.

Additionally, some switchgear diagnostic methods, for example partial discharges (see section 3.3.6), can be implemented with both periodic measurements and continuous monitoring depending on the specific needs.

2.6 MEANING OF USEFULNESS OF DIAGNOSTIC METHOD

Usefulness is generally understood as practical worth or applicability.

Generally, non-intrusive diagnostic methods are simpler to apply than their counterparts. However, the outputs may be less direct, more qualitative and may involve larger approximations or uncertainties. The usefulness of such diagnostic methods can be questioned.

Judging the usefulness of a given method should take into account technical, economic, organizational, social, environmental, and legislative aspects. In this brochure, JWG A3.32 focused on technical aspects in a common context that assumes:

- a need for maintenance schedule optimization and condition based maintenance
- an added value from switchgear's life extension, from postponing of equipment replacement and from higher switchgear utilization
- a requirement for adequate failure investigations
- a requirement to protect the environment especially to reduce SF_6 manipulations

- a non-zero tolerance to risk in asset management

In order to establish the usefulness of diagnostic methods, JWG A3.32 recommends that appropriate cost-benefit analyses be conducted. 'Benefits' of the diagnostic method can be expressed in terms of condition indicators and potential achievable diagnosis. On the other hand, 'costs' encompass the total expenses, efforts, and risks involved in the elaboration and realization of the diagnostic.

Many condition indicators are commonly used for switchgear diagnosis (Table 5-1). However, often the outcome of a non-intrusive diagnostic method may be expressed in some other form, with, possibly, less accuracy and certitude. In such cases, a higher tolerance to risk is required to decide on maintenance, repair or replacement of the switchgear. Even when applying the finest intrusive sensors or when proceeding with direct inspections, total guarantee that failures won't happen is not possible; a risk of zero does not exist. Without a doubt, a lack of accuracy may increase the risk of a wrong diagnosis of the switchgear's condition. However, the final decisions are often taken on the basis of other inputs and the overall risk of a wrong decision may not increase as much. Nevertheless, this increase in risk should be separately analyzed for every particular scenario involving a given diagnostic method, particular switchgear, and its duty in the grid.

The 'benefit' of a given diagnostic method can also be evaluated with appropriate statistical models and failure mode analysis as discussed in Chapter 5.

Evaluating the 'cost' of a diagnostic method is much more direct. Each utility may consider different levels of detail, but the evaluation should at least consider the following:

- direct charges (instruments, sensors, software, licenses, labor, professional services, etc.)
- costs of implementation - how the results fit the organization decision process and the review of maintenance policies
- cost of an outage (for off-service diagnostic methods)
- costs related to environmental considerations or risks (SF_6 or oil leaks, …)
- costs related to damaging the switchgear (for intrusive methods requiring dismantling)
- costs related to results interpretation (supplementary expertise or software)

Generally, one would expect a non-intrusive method to be less costly than an equal-benefits intrusive method.

2.7 SUMMARY

General terms such as switchgear condition, diagnostic method, condition measurement, condition indicators and diagnoses have been discussed. The latter is considered as the end use of the diagnostic process.

The definition of non-intrusive diagnostics is explained in detail and the maturity levels as well as application modes of a diagnostic method are introduced. These terms are used widely in Chapter 3.

Finally, the approach for evaluating the usefulness of non-intrusive diagnostic methods as a cost-benefit analysis is introduced and is further developed in Chapter 5.

3. CONDITION ASSESSMENT METHODS IN SWITCHGEAR

3.1 INTRODUCTION

Among the large variety of condition assessment methods for switchgear, which are dealt with in technical and scientific publications, this technical brochure (TB) mainly focusses on those methods considered "non-intrusive" with respect to the integrity of the device according to the definition given in Chapter 2. These methods are addressed in great detail in this chapter. Additionally, further methods categorized "minimally intrusive" are covered to a certain extent. Each method is analyzed regarding its technical background, experience, maturity and its value for condition assessment.

3.2 SUMMARY OF METHODS

The total number of discussed methods is 55. To have a better overview of all methods and to enable an analytical way of working, they are divided in different groups by categorizing their characteristics.

All different methods can be categorized by their degree of intrusion in the switchgear, iincluding installation as well as operation. Figure 3-1 represents how many of the 55 discussed methods are installed in an intrusive, minimally intrusive or non-intrusive way. 41 of the 55 methods (about 75 percent) are non-intrusively and 9 methods (about 16 percent) are minimal intrusively installed. The remaining 5 methods (about 9 percent) are installed intrusively.

However all 55 methods operate non-intrusively. This emphasizes the general concentration on non and minimally intrusive methods in this TB.

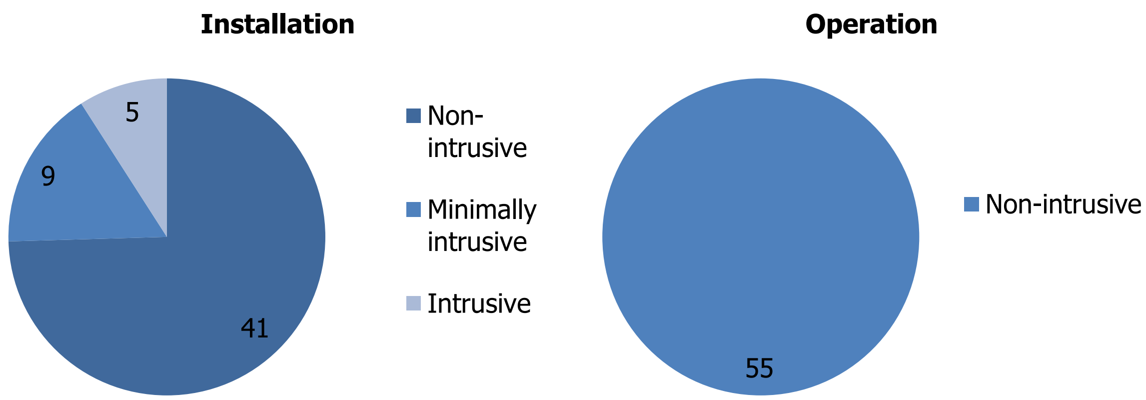


Figure 3-1: Circuit breaker integrity in installation

All diagnostic methods can be further categorized by the status of the switchgear while the method is used. If the method is installed and applied while the switchgear is in an operating status, the technique is classified as "In-Service". On the other hand, if the method is installed and applied while the switchgear is temporarily disconnected from the grid, it is categorized as an "Off-Service technique".

Figure 3-2 shows the distribution of "In-Service" and "Off-Service" techniques, further divided into the installation and operation process. Figure 3-2 (left) illustrates, that only 21 of the 55 methods (about 38 percent) are installed "In-Service", therefore 34 of the analyzed methods (about 62 percent) require, that the Circuit Breaker is disconnected from the grid during the installation process. However, Figure 3-2 (right) shows that 39 methods (about 71 percent) operate "In-Service", and accordingly only 16 methods (about 29 percent) operate "Off-Service".

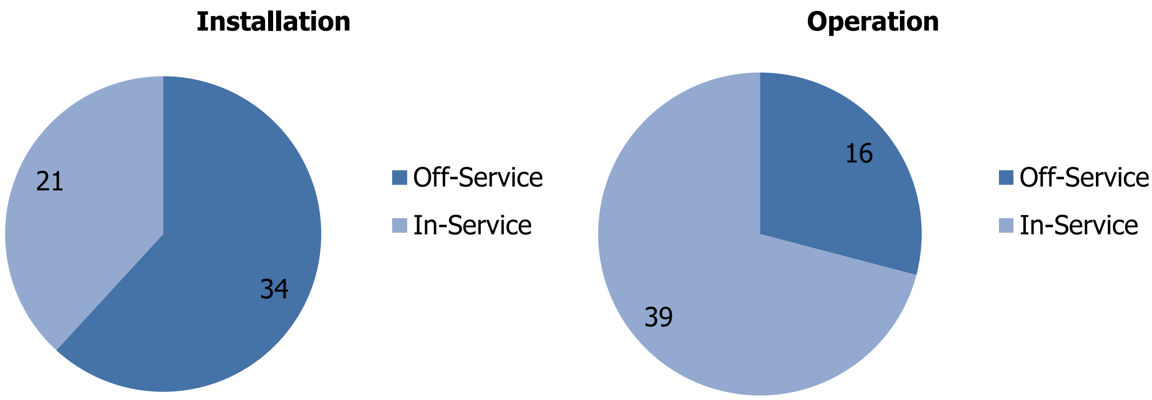


Figure 3-2: Left: Grid integrity in installation Right: Grid integrity in operation

The different methods analyzed by the JWG A3.32 are described in publications, white papers and brochures. Generally a large spread from purely theoretical concepts, prototypes at the laboratory stage, to well proven products and methods with considerable experience in the field is observed. The degree of maturity is split into seven categories; as shown in Table 2-2.

To get an overview of the degree of maturity, a pie chart of the distribution of the different degrees for the seven categories is diagrammed in Figure 3-3. However none of the 55 methods is still in the "Theoretical Concept" category. In contrast to this, 22 of the methods (40 percent) already have commercial products available. This illustrates that the general degree of maturity overall is quite advanced.

Additionally 8 methods (about 15 percent) belong to the sector "Standard practice in the field" and another 8 methods (about 15 percent) are currently tested in the field. Furthermore only 5 methods (about 9 percent) belong to the category "Mature product available". In addition there are also 5 methods (about 9 percent) that have a prototype available and another 7 methods (about 13 percent), which are still in "Research and Development-Activity".

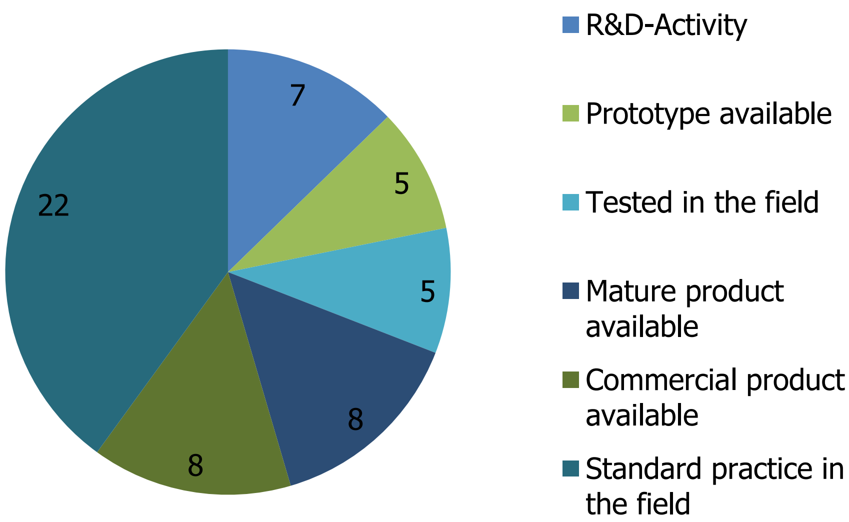


Figure 3-3: Distribution of the degree of maturity

3.3 DETAILED DESCRIPTION OF THE METHODS

In the following overview figure and table (Figure 3-4 and Table 3-1) the structure of the chapter is shown. The discussed methods can be classified in three different categories: Primary Path, Mechanical and Control. The Primary Path category includes switching and insulation methods.

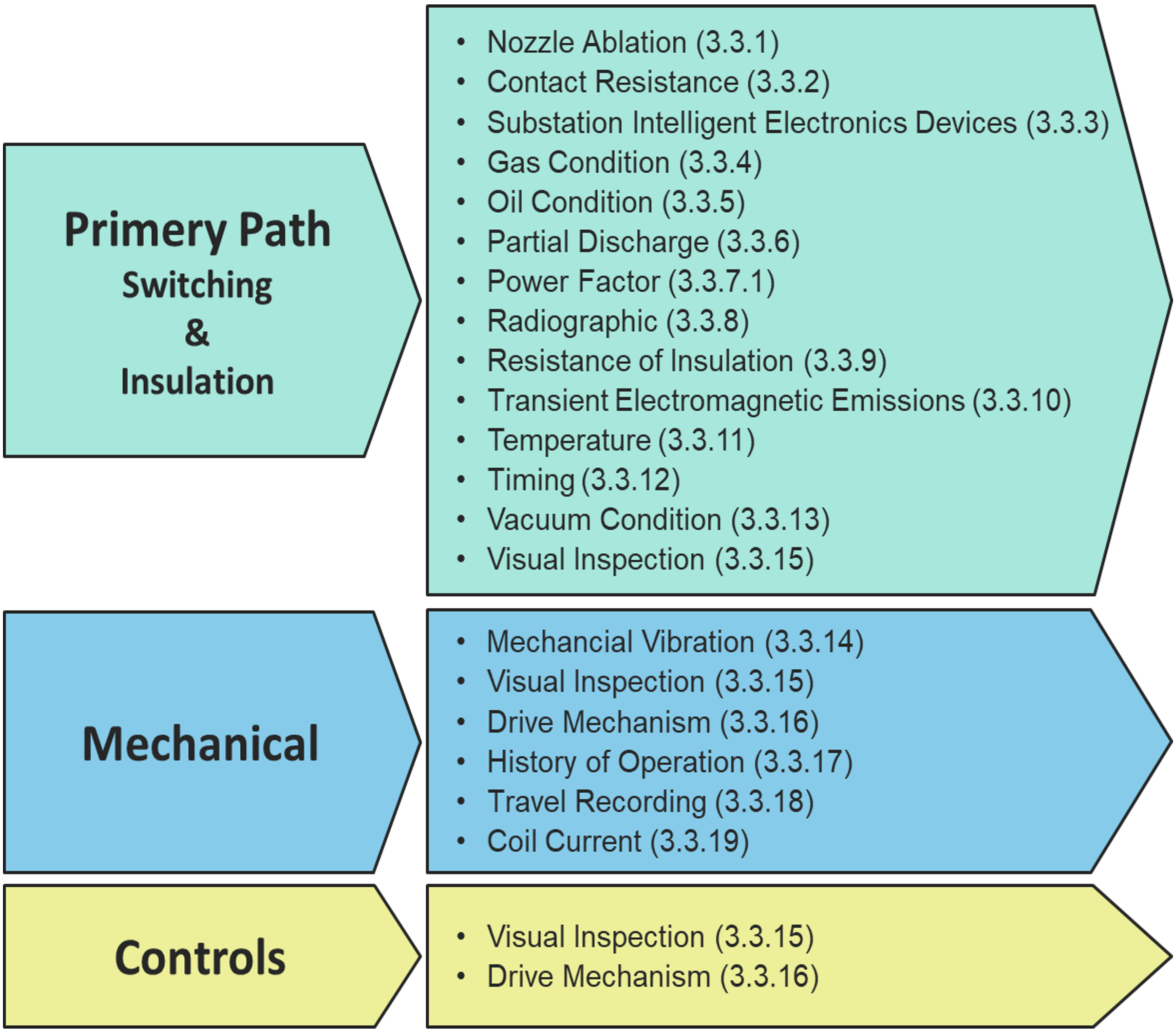


Figure 3-4: Overview of the methods

Table 3-1: Overview Table

		Scope	Grid integrity		CB integrity		Degree of Maturity	Voltage-Level	Insulation and Switching Medium
			Instal-lation	Opera-tion	Instal-lation	Opera-tion			
1		***Nozzle Ablation***							
	1.1	Transient Pressure Profile	off	off	non	non	■■■□□□□	HV	Gas
2		***Contact Resistance***							
	2.1	Static Contact Resistance Measurement	off	in	non	non	■■■■■■■	HV+MV	All
	2.2	Dynamic Contact Resistance Measurement	off	off	non	non	■■■■■■■	HV+MV	All
3		***Substation Intelligent Electronics Devices***							
	3.1	Digital Fault Recorders (DFR)	in	in	non	non	■■■■□□□	HV+MV	All
	3.2	Digital Protection Relays (DPR)	in	in	non	non	■■■■□□□	HV+MV	All
4		***Gas Condition***							
	4.1	Density switch, alarms	in	in	non	non	■■■■■■■	HV+MV	Gas
	4.1	Density switch, trending software	in	in	non	non	■■■■■■■	HV+MV	Gas
	4.1	Camera	in	in	non	non	■■■■■■■	HV+MV	Gas
	4.2	Measurement of Humidity	off	in	min intr	non	■■■■■■■	HV+MV	Gas
	4.3	Measurement of decomposition products	off	off	min intr	non	■■■■■■■	HV+MV	Gas
	4.4	Measurement of SF_6 Percentage	off	off	min intr	non	■■■■■■■	HV+MV	Gas
5		***Oil Condition***							
	5.1	Bulkoil, Quality	in	in	non	non	■■■■■■□	HV+MV	Oil
	5.1	Bulkoil, Metals	in	in	non	non	■■■■■■□	HV+MV	Oil
	5.1	Bulkoil, DGA	in	in	non	non	■■■■■■□	HV+MV	Oil
	5.1	Minimum oil, Quality	off	off	non	non	■■■■■■□	HV+MV	Oil
	5.1	Minimum oil, Metals	off	off	non	non	■■■■■□□	HV+MV	Oil
	5.1	Minimum oil, DGA	off	off	non	non	■■■■■□□	HV+MV	Oil
6		***Partial Discharge***							
	6.1	UHF method	off	in	intr	non	■■■■■■■	HV+MV	Gas / Solid
	6.2	HF/VHF method	in	in	intr	non	■■■■■■□	HV+MV	Gas / Solid

		Scope	Grid integrity		CB integrity		Degree of Maturity[2]	Voltage-Level	Insulation and Switching Medium
			Instal-lation[1]	Opera-tion[1]	Instal-lation[1]	Opera-tion[1]			
	6.3	TEV method	in	in	non	non	■■■■■■■	HV+MV	Gas / Solid
	6.4	Acoustic method	in	in	non	non	■■■■■■□	HV+MV	Gas / Solid
7		***Power Factor / Capacitance***							
	7.1	Power Factor Measurement	off	in	min intr	non	■■■■■■■	HV+MV	All
8		***Radiographic***							
	8.1	X-Ray	off	off	non	non	■■■■■■■	HV+MV	All
9		***Resistance of Insulation***							
	9.1	Insulation Resistance Measurement	off	off	non	non	■■■■■■■	HV+MV	All
10		***Transient Electromagnetic Emissions***							
	10.1	TEE detection with UHF antennas	In	In	non	non	■■■■■□□	HV	All
	10.2	TEE detection with capacitive sensors	In	In	non	non	■■■□□□□	HV	All
	10.3	TEE detection with PD couplers	In	In	non	non	■■□□□□□	HV	All
11		***Temperature***							
	11.1	Infrared (IR) Cameras	off	in	non	non	■■■■■■■	HV+MV	All
	11.2	Fiber Guided IR Temperature Sensors	off	in	intr	non	■■■■■□□	HV+MV	All
	11.3	Surface Acoustic Wave (SAW)	off	in	intr	non	■■■■■□□	HV+MV	All
	11.4	Wireless Temperature Sensors	off	in	intr	non	■■■□□□□	HV+MV	All
12		***Timing***							
	12.1	Circuit Breaker Timing of Main Contacts	off	off	non	Non	■■■■■■■	HV+MV	All
	12.2	Circuit Breaker Timing with Protective OCB Relays	in	in	non	non	■■■■■□□	HV+MV	All
	12.3	Circuit Breaker First Trip Analyzer	in	in	min intr	non	■■■■■■■	HV+MV	All
13		***Vacuum Condition***							
	13.1	Mobile Magnetron (coils)	off	off	non	non	■■■■□□□	HV+MV	Vacuum
	13.1	Mobile Magnetron (perm. magnets)	off	off	non	non	■■□□□□□	HV+MV	Vacuum
	13.2	Dielectric Vacuum Testing	off	off	non	non	■■■■■■■	HV+MV	Vacuum

		Scope	Grid integrity		CB integrity		Degree of Maturity[2]	Voltage-Level	Insulation and Switching Medium
			Instal-lation[1]	Opera-tion[1]	Instal-lation[1]	Opera-tion[1]			
	13.3	Vacuum Gauges	off	in	non	non	■■■□□□□	HV+MV	Vacuum
	13.4	Mechanical Monitoring	off	in	non	non	■■■■□□□	HV+MV	Vacuum
	13.5	Partial Discharge	off	in	min intr	non	■■■□□□□	HV+MV	Vacuum
	13.6	Field emission	off	off	non	non	■■□□□□□	HV+MV	Vacuum
	13.6	Current interruption	off	off	non	non	■■□□□□□	HV+MV	Vacuum
	13.6	Sound waves	off	in	min intr	non	■■□□□□□	HV+MV	Vacuum
	13.6	Light emission	off	off	non	non	■■□□□□□	HV+MV	Vacuum
14		***Vibration***							
	14.1	Measurement of Arc Contact Ablation	off	in	non	non	■■□□□□□	HV+MV	Gas
	14.2	Detecting of Mechanical Anomalies	off	in	non	non	■■■■■□□	HV+MV	All
15		***Visual Inspection, control and auxiliary circuits***							
	15.1	Non-intrusive Visual inspection	in	in	non	non	■■■■■■■	HV+MV	All
	15.2	Controls and auxiliary circuits	in	in	non	non	■■■■■■■	HV+MV	All
16		***Drive Mechanism***							
	16.1	Motor Position Torque Measurement	off	in	non	non	■■■■■□□	HV+MV	All
	16.2	Spring Stored Energy Status	off	in	min intr	non	■■■■□□□	HV+MV	All
17		***History of Operation***							
	17.1	I^2T Recording	in	in	non	non	■■■■■■■	HV+MV	All
	17.2	Number of fault Operations	in	in	non	non	■■■■■■■	HV+MV	All
	17.3	Mechanical Operations Counter	off	in	non	non	■■■■■■■	HV+MV	All
18		***Travel Recording***							
	18.1	Dynamic Contact Travel	off	in	min intr	non	■■■■■■□	HV+MV	All
19		**Coil Current**							
	19.1	Measurement and Analysis of coil current	in	in	non	non	■■■■■■■	HV+MV	All

3.3.1 Nozzle Ablation

SF_6 gas circuit breaker manufacturers require disassembly and visual inspection of the interrupter main contacts, arcing contacts and gas nozzles to determine their condition and if replacement is necessary. Historically these inspections have been based on time, electrical operations, fault operations or a combination. For example, after ten operations at rated short-circuit breaker operations, 2000 electrical operations or twelve years for single pressure SF_6 dead tank circuit breakers, a contact inspection is recommended.

As these single pressure SF_6 gas circuit breakers have become the industry standard, over the past thirty years, these maintenance intervals have been reached. However, the resulting inspections did not prove to be good indicators of contact and nozzle wear. The inspections were costly, inconsistent and had the potential for damage due to the inherent risks involved in an internal inspection performed in the field.

3.3.1.1 Transient Pressure Profile

APPLICATION

Up to now nozzle ablation, due to the thermal effects of the arc while switching, could not have been determined without opening the gas chamber. Now, a minimum-invasive and offline diagnostic technique has been developed to assess the wear of the insulation nozzle inside the switching chamber of a CB [Wetzeler2016]. The pressure signal is investigated regarding characteristic features which yield information for the determination of the switching chamber condition. A machine learning algorithm applying the k-Nearest-Neighbor-method is used for the determination of the nozzle and electrode condition, while the characteristic features are utilized as input parameters. Thus, it is possible to classify new unknown measurements with an already known data basis. The method can be used in high voltage CBs.

MODE OF APPLICATION

Periodic Measurement	✔	Continuous Monitoring

THEORETICAL BACKGROUND

Different connection points are possible for the connection of the pressure sensor. A single valve is located at the bottom of each pole. By using this connection for the pressure sensor, the pressure wave of only one pole is considered. During standard operation, the three poles are connected by copper pipes. The main filling valve is located inside the chassis of the circuit breaker and links all three poles. While using the main filling valve as the connection port for the pressure sensor, the measured signal is the superposition of the three single pressure signals.

For the pressure measurements, a high sensitive piezoelectric pressure sensor with a suitable charge amplifier is used (Figure 3-5).

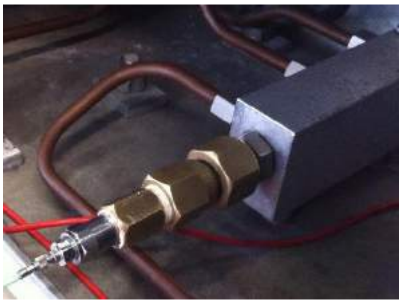


Figure 3-5: Connection point with pressure sensor (main filling valve)

The raw data of the pressure measurement is cut from the start of the switching operation until the end of the 6th oscillation. This signal can be processed with and without filtering. A fast Fourier transformation is applied to the unfiltered signal. Additionally, the signal is filtered with a 100 Hz low-pass filter. Figure 3-6 and Figure 3-7 show the pressure history and frequency spectrum.

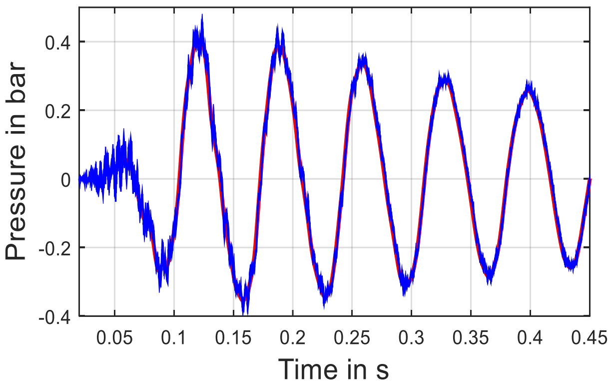


Figure 3-6: Raw data of a measurement at the main filling valve in original condition (blue), filtered signal (red)

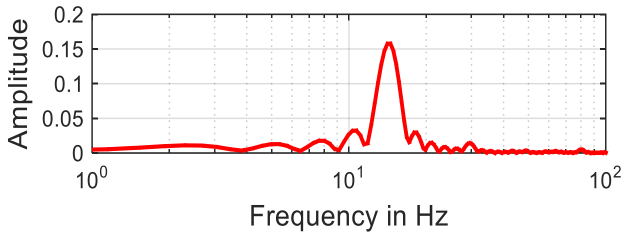


Figure 3-7: Frequency spectrum of raw data

Several markers can be derived from the filtered and unfiltered pressure signal. These markers capture characteristics of the different measurement signals and can be used to identify the nozzle conditions. Due to the wide scattering of the markers a simple matching of the different ablation cases with the markers is not possible. For this reason, the k-Nearest-Neighbor Algorithm is used for the evaluation. The Algorithm generates a base n vector for each measurement, where n is the number of markers. The distance calculation between two vectors is based on the Euclidean distance with an additional weighting with the variance [Sra2012].

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

The method is easy to apply because an already existing filling valve can be used to connect a pressure sensor. However, it is difficult to diagnose the nozzle condition because the condition indicators (markers) values are widely scattered.

The marker scales are optimized with a sensitivity analysis [Wetzeler2016]. These can be used to classify an ablated nozzle, but one marker alone does not bear enough information for all cases. The sum of all seven markers in combination with a classification algorithm is required. Different classification algorithms have been tested with the result that the k-Nearest-Neighbor Algorithm with the Standard Euclidean distance holds the lowest error rate of less than 0.9% in cross validation. The combination of markers and k-Nearest-Neighbor Algorithm is used to classify field measurements from different circuit breaker types. This can be performed without any error for the regarded circuit breaker measurements.

3.3.2 Contact Resistance

The contact resistance is measured on all types of MV and HV circuit breakers to validate the current carrying contacts. This ensures their ability to carry the rated current within specified temperature rise.

Failing that will result in overheating of the contacts which can lead to contact welding or insulation degradation [CIGRE_167_2000]

3.3.2.1 Static Contact Resistance Measurements

APPLICATION

The static contact resistance measurement is a non-intrusive measurement performed while the CB is offline. The contacts are closed and the test leads are applied to the primary path on both sides. For safety reason it is recommended to ground at least one side [Renaudin2015].

Typical measured anomalies are:

- Increased resistance; typical value between 10 to 100 micro Ohm
- Fluctuating resistance
- High variations between similar contact systems (i.e. between phases)

The contact degradation process is a self-accelerated process which slowly develops over years until it finally speeds up dramatically before it causes a failure. Because of this behavior, it is sufficient to perform this test during regular maintenance work and commissioning. [CIGRE_167_2000]

MODE OF APPLICATION

Periodic Measurement ✔	Continuous Monitoring

THEORETICAL BACKGROUND

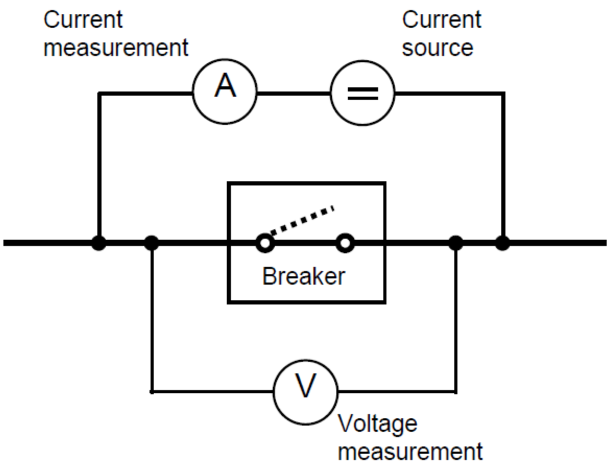


Figure 3-8: Four point resistance measurement [CIGRE_167_2000]

The most common offline test method for contact resistance is the four point resistance measurement. See Figure 3-8 for a typical wiring setup. There the applied DC current is separated from the voltage drop measurement. This separation results in a higher accuracy because the contact resistance of the current leads can be neglected. Recommended injection current levels are at least 50 A (IEC 60694) or 100 A (ANSI)[Bhole2015] up to the rated current of the equipment. Occasionally there might be contact grease or decomposition products present at the contact surfaces and thus causes a lower resistance value at higher currents. [CIGRE_167_2000]

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

On regular CB designs there is low effort needed to perform a contact resistance measurement on a CB which is already out of service for maintenance work. However, on gas insulated switchgear (GIS) or dead-tank design additional aspects have to be considered.

In order to access the primary path on a GIS, insulating ground switches are usually required. As the CB is closed and grounded on both sides, the grounding shunt on one side can be removed and the conductor accessed. For an example see Figure 3-9.

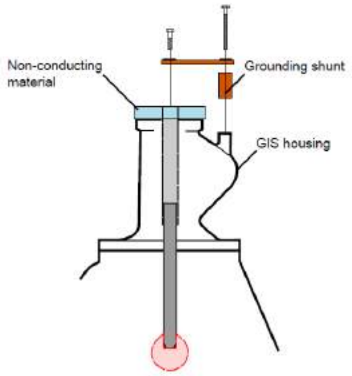


Figure 3-9: Insulating grounding switch [OMICRON2017]

On a dead tank design and GIS, it is common to have current transformers (CT) in the measuring path. This has to be considered when applying DC current because the coils have to be saturated before the measurement is performed and afterwards have to be demagnetized. [Sweetser2016]

3.3.2.2 Dynamic Contact Resistance Measurements

APPLICATION

The Dynamic Contact Resistance Measurement (DCRM) is usually applied at medium and high voltage on SF_6 circuit-breakers, which are characterized by two sets of parallel contacts, namely the arcing and the main contacts. During the opening operation, main contacts separate first and the current is commutated to the high-resistance arcing contacts, which separate a few milliseconds later. Thus, measuring the contact resistance during the opening operation reveals the condition of the arcing contact whereas measuring the contact resistance while the CB is closed shows the condition of the main contacts.

The measurements are usually done during an opening operation and the test leads are applied to the primary path on both sides.

Anomalies which can be detected in a dynamic contact resistance measurement by changes in the resistance characteristic are

- arcing contact wear [CIGRE_167_2000]
- abnormal current path current. See Figure 3-12
- misalignment and wrong assembly in the interrupter. See Figure 3-13

These changes can be detected by comparing with previous measurements, i.e. during commissioning, or by comparing between the three phases. Figure 3-10 shows an example where one of the DCRM has a significantly shorter arcing contact trace. This indicates that the arcing rod length has dramatically been reduced i.e. because of strong arc erosion.

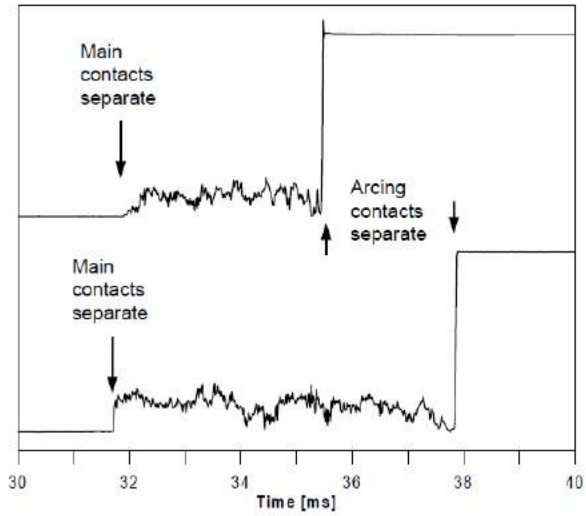
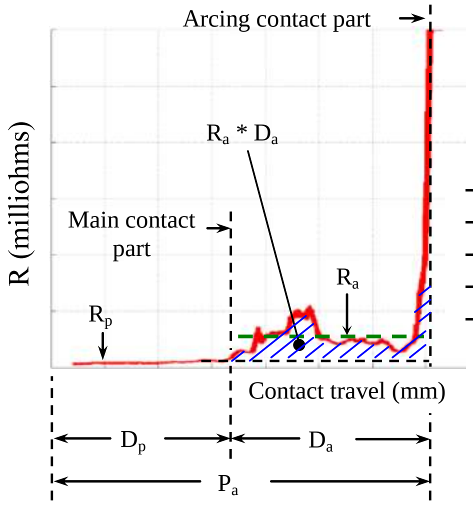


Figure 3-10: Two examples of DCRM measurement performed on the same CB [CIGRE_167_2000]

In combination with contact travel measurements, a DCRM provides detailed information about the condition of the contact. A typical dynamic resistance plotted as a function of contact travel is shown in Figure 3-11. From this representation, it is possible to calculate parameters useful for diagnostics, such as the main and arcing contact wipes and the average arcing resistance.



- R_p (µΩ): Average main contact resistance
- R_a (µΩ): Average arcing contact resistance
- D_p (mm): Main contact wipe
- D_a (mm): Arcing contact wipe
- P_a (mm): Position of the breaker contacts at the arcing contact part

Figure 3-11: Parameters to be extracted from the dynamic contact resistance curve [Landry2004]

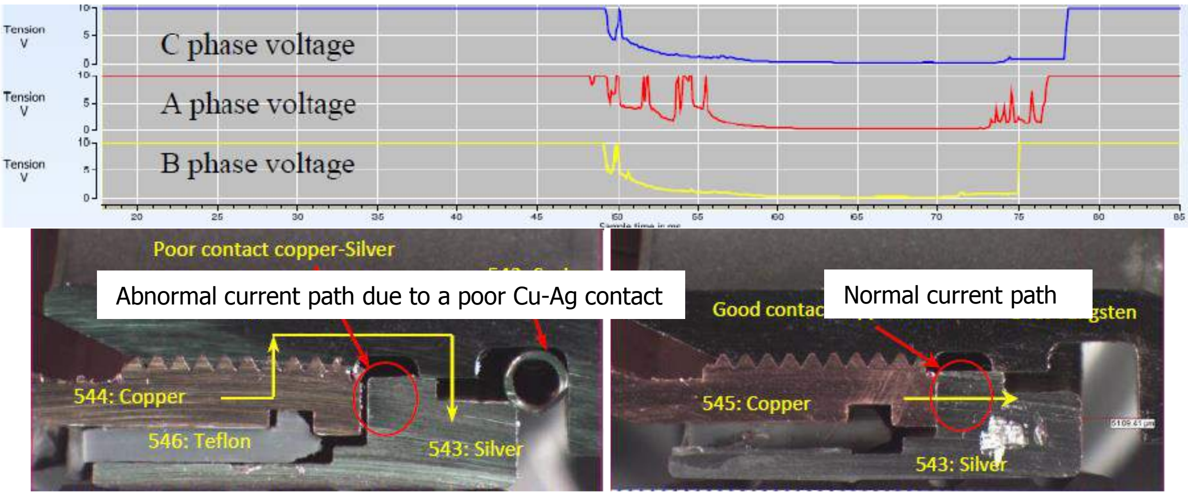


Figure 3-12: Abnormal current path detected by the DCRM method [Lalonde2012]

Figure 3-13: Wrong assembly; 31.5 kA arcing contact instead of 40 kA arcing contact used [Sodha2012]

MODE OF APPLICATION

Periodic Measurement	✔	Continuous Monitoring

THEORETICAL BACKGROUND

The DCRM test is usually performed by applying the four point resistance measurement. A first pair of cables is used for injecting a high DC current in the CB interrupter, while the other pair of cables is used for measuring the voltage drop across the CB contacts. See Figure 3-8 on how the wires are usually applied on both sides of the contact.

Recommended injection current levels are at least 50 A (IEC 60694) or 100 A (ANSI)[Bhole2015] up to the rated current of the equipment. Some studies recommend to use at least 700 A [Stanisic2010]. Occasionally there might be contact grease or decomposition products present at the contacts surface and thus causes a lower resistance value at higher currents.

Another parameter affecting the measurement accuracy is the breaker contact speed (low or rated). When using a lower breaker contact speed, the DCRM results are more repeatable and it is easier to distinguish when the main contact part occurs. The downside is that in some breakers, the adjustment of the breaker speed is intrusive.

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

DCRM is a very mature technology which has been practiced in the field for over a decade and there are multiple manufacturers of circuit breaker analyzers which include a DCRM measurement.

Despite the relative simplicity of the method, an adequate interpretation of the DCRM results may become complex and some diagnostic misinterpretations are thus possible. In fact, the arcing contacts resistance can be strongly influenced by many factors, such as:

- the injected DC current intensity
- fast changing force at the contact fingers causes a fast changing resistance value; in particular during the closing operation
- the possible presence of metallic fluorides deposited on the contacts
- the possible poor connections between current cables and the CB terminals

DCRM can postpone maintenance such as contact inspection or replacement, which is especially costly for SF_6 circuit breakers.

3.3.3 Substation Intelligent Electronics Devices

The use, capability and reliability of multifunctional intelligent electronic devices (IED), such as Digital Fault Recorders (DFR), Digital Protective Relays (DPR), Sequence of Event Recorders (SER), Phasor Measurement Units (PMU) or Power Quality Monitors (PQM), are growing considerably in today's substation. They play a vital role in decision support for operation and maintenance of the grid. The analysis putting into synergy several IEDs will generally give the best results [Fecteau2005, Allen2005, CIGRE_424_2010, El-Hadidy2011].

DFRs and DPRs are especially useful for CB diagnostics due to their possibility of producing oscillography recordings of voltages, currents and other signals associated with the CB operation. The analysis essentially consists of the examination of the correctness of the protection and breaker responses.

The primary functions of DPR are to detect the conditions which can cause damage to equipment, danger to personnel or to the proper operation of the power system and to eliminate these conditions as quickly as possible by sending a signal to the circuit breaker. The recording of some monitored conditions is only its secondary function. Thus, the storing capacity is limited and, in general, only the fault data are saved.

In contrast, the primary functions of DFR are to gather data required for detection of abnormal conditions of the grid and the post event analysis following a power system disturbance. The DFR will also obtain time and system correlated information on performance of the CB and DPR. Some regulatory organizations require that utilities maintain such devices. Beside the storing capacity, the key issue is triggering capability and setting. Usually, DFRs have advanced triggering options and their setting is more sensitive than that of DPRs [Fecteau2005, El-Hadidy2011].

3.3.3.1 Diagnostics using Digital Fault Recorders (DFR)

APPLICATION

This method uses DFR to record system current and voltage oscillograms during every circuit breaker switching operation for a period of time around three to five seconds. The collected data is sent to a server where dedicated software does the analysis. The method can be applied to any switchgear where DFR is available and can be programmed adequately i.e. trigger and store the data from any switching operation.

MODE OF APPLICATION

Periodic Measurement	**Continuous Monitoring** ✔

THEORETICAL BACKGROUND

As reported in the literature, the following information can be retrieved from oscillograms to different extent and precision:

1. occurrence of prestrikes, re-ignition and restrikes

2. some operation timing parameters, including discrepancies between poles
3. number of operations (fault, normal load, no load)
4. cumulative amount of the arcing energy I^2T
5. improper operation of pre-insertion resistor [El-Hadidy2011a]

Prestrikes, re-ignition and restrikes across circuit breaker switching contacts are happening when the dielectric withstand is lower than the actual voltage between the contacts. Prestrikes occur during closing and correspond approximately to the current initiation. DFR oscillograms usually do not allow analysis of prestrikes by interrupter in series and of multiple prestrikes (Table 3-2 in section 3.3.10.1).

Re-ignitions and restrikes are happening on opening and the underlying causes are related to

- CB, i.e. weak dielectric property or slow operation
- network, i.e. overvoltage due to reactive load

The application of transient analysis of oscillograms to detect circuit breaker restrikes is reported in the literature [Kocis2007, El-Hadidy2011a, Allen2005, CIGRE_424_2010].

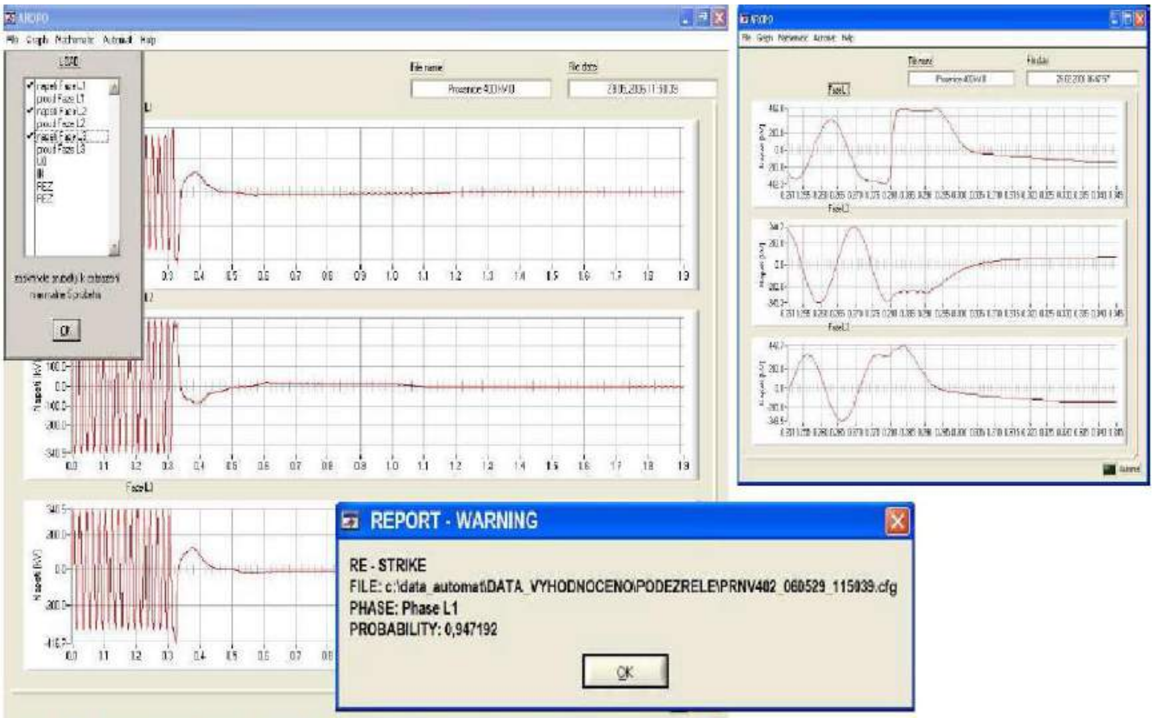


Figure 3-14: Recording of CB restrike [Kocis2007]

Current and voltage oscillograms allow evaluation of arcing time and make time per pole (as defined in IEC 62271-100) if the protection signal is available directly in the DFR [Kocis2007] or can be accurately correlated by analysis software [Allen2005].

Software which can automatically evaluate points 1 to 4 above is reported in the literature [Kezunovic2003, Kocis2007, Svancar2015]. However, considering the complexity of systems involved and the number of possible cases, this method cannot be considered as mature.

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

The following constraints need to be considered when using DFR oscillograms for CB diagnostics: characteristic of current transformers (CT), voltage transformers and other sensors, saturation of CT, sampling rate, which could vary from 1 kHz to 20 kHz, network configuration and type of electrical load, type of CB as well as storage capacity of the DFR and format of the data. The reliability of DFRs and measuring systems is not secured and its integrity should be continuously validated [Fecteau2005]. Conventional CTs have limited bandwidth and application of a Rogowski coil will improve the precision of oscillograms [Dupraz2007].

Using the method described in Section 3.3.12.1, the timing is evaluated for each interrupter, while using DFR the timing is evaluated only for the entire pole.

Opening time is defined here as the mechanism time from the moment the trip signal is applied to the CB mechanism till the moment when the contacts part.

3.3.3.2 Diagnostics using Digital Protection Relays

APPLICATION

There is a variety of DPRs fulfilling different protection duties which can also record oscillograms. DPR's data can be used in diagnostics of any switchgear.

MODE OF APPLICATION

Periodic Measurement	**Continuous Monitoring** ✔

THEORETICAL BACKGROUND

DPR can accomplish various analysis tasks such as: CB timing (see also Section 3.3.12.2 for a specific example), arcing time and I^2T calculation, auxiliary contacts monitoring, trip coil continuity monitoring and counting of the number of operations [Dalke2004, Allen2005, Desai2012]. With additional software the DPR data can be used as a CB monitoring tool [Sheng2005, Tang2006]. The DPR can also be applied for flashover condition protection and analysis and as a real-time monitoring and maintenance tool [Sandoval2004].

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

Similar constraints as for DFR above needs to be considered using DPR in addition to the inherent limitations of DPR (lower sampling rate and storage capacity). It should also be noted that adding extra duties on DPR could compromise its primary function which is network protection.

3.3.4 Gas Condition

The condition of the gas used within switchgear needs to be monitored throughout the lifetime of the asset. Each manufacturer will specify a gas density at which the switchgear should be maintained throughout its useful life. Any loss of this gas could result in reduced insulation and breaking capability of the switchgear. The most common way to monitor this pressure is via a density switch mounted to the gas compartment. A newer technique being used is infrared technology to both detect and locate the source of leaks. Gas quality is most commonly measured at acceptance or commissioning stage and then during the in-service life of the switchgear where sampling ports are available. In general there are 3 categories; humidity, percentage and decomposition products.

3.3.4.1 Gas Density

APPLICATION

Gas filled switchgear at all voltage levels are generally equipped with a two stage temperature corrected gas pressure (density) switch which will trigger when the pressure drops below predefined thresholds. The first threshold is most commonly used as an alert, while the second threshold will be used as either an operation block or a circuit breaker trip command. The reason for this is that the breaking capacity of a circuit breaker is dependent on the gas density in the breaking chamber, once the density falls below a certain value the circuit breaker may not be able to isolate the circuit under normal or fault circumstances.

There are also newer systems which permanently monitor and trend the pressure and temperature and will alarm when it senses a loss of pressure at the recorded temperature.

Lastly there are portable cameras which can be used to detect the exact location of the leak. This practice is most commonly used once a low gas alarm is received.

MODE OF APPLICATION

Density switch	Periodic Measurement	**Continuous Monitoring** ✔
Pressure transducer trending software	Periodic Measurement	**Continuous Monitoring** ✔
Camera	**Periodic Measurement** ✔	Continuous Monitoring

THEORETICAL BACKGROUND

One of the most common temperature corrected gas pressure (density) switches is the bourdon tube type. The gas enters the tube at the base, see Figure 3-15. At the other end of the tube an end piece is fitted to an adjustable link. As the gas enters the bourdon tube it will begin to unwind due to the internal pressure. This small movement is matched with a rotational pointer movement of which normally open or normally closed contacts are also attached in order to connect local alarms.

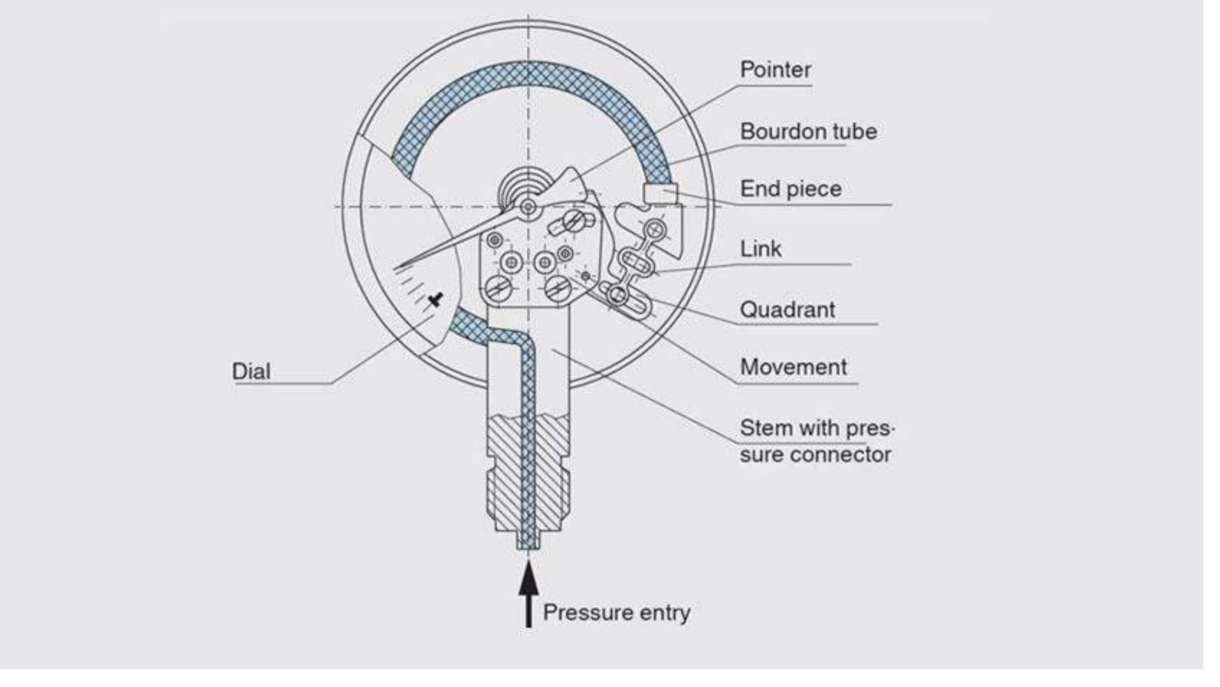


Figure 3-15: Bourdon tube [Wika2017]

Trending of pressure and temperature is more common practice today. Use of sensors in place of, or in conjunction with conventional density monitors can provide a more accurate reading of the gas pressure levels and provide trending information allowing analysis of the time remaining before reaching critical levels. This also helps reduce the environmental impact of SF_6 leaks where it is used as the insulating medium.

Lastly optical gas imaging cameras are available on the market which allows the operator to detect the exact location of the leak without the need to remove the circuit breaker from service. When used on SF_6, the camera matches the spectral response of the camera to the "peak" spectral absorption of SF_6, see Figure 3-16 below.

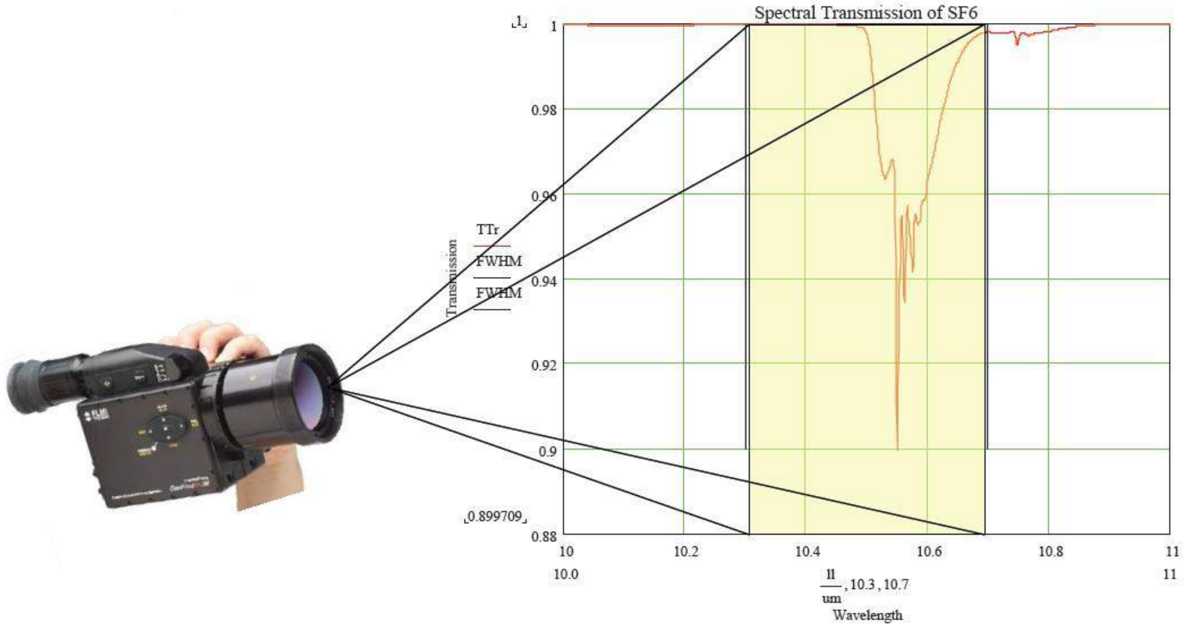


Figure 3-16: Flir SF_6 camera[Czerepuszko2007]

This results in an image which shows the SF_6 leak as a black cloud.

DEGREE OF MATURITY

Density switch, alarms	
Pressure transducer, trending software	
Camera	

EASE OF USE AND CONSTRAINTS

All methods mentioned above are non-intrusive, the bourdon tube type monitor provides two stage alarms which in most cases will allow time for the circuit breaker to be taken out of service in a timely manner and topped up or repaired as necessary. The downside to this is that a certain amount of SF_6 will have leaked before the alarm is activated. Sometimes there will be temperature differences between the poles on a live tank circuit breaker and the density switch, this can lead to alarms being activated at cooler times such as late night or early morning.

Trending of the SF_6 density provides an earlier indicator that a leak is present on the circuit breaker and allows the system operator to decide how to deal with the leak in a timely manner, such as isolate in advance of high load periods rather than risk an alarm at these times.

The optical SF_6 imaging camera is a very convenient way to detect the location of leaks from a safe distance. The camera will detect almost all leak locations which allows for spare parts to be purchased in advance of removal from service for the repair [CIGRE TB 430]. The first versions of this camera were very expensive whereas the newer models have been reduced in price and as such are becoming more commonly used.

3.3.4.2 Measurement of Humidity

APPLICATION

Humidity from the ambient air can diffuse into the interior of the SF_6-filled compartment through seals such as O-rings and gaskets. In order to remove water vapour, desiccant bags are placed into the compartments, to absorb the humidity.

However, as the humidity might influence / reduce the properties of the gas, it is very important, to measure the humidity in the SF_6-filled compartments of T&D switchgear to ensure the proper function of the devices.

MODE OF APPLICATION

Method	Periodic Measurement	Continuous Monitoring
Chilled Mirror Method	✓	
Capacitive Polymer Method	✓	✓
Alluminum Oxide Method	✓	

THEORETICAL BACKGROUND

There are different technologies available for humidity measurement: For the Chilled Mirror technology the dew or frost point of a gas is measured, using the following principles. Light shines onto a polished mirror surface, the temperature of which is controlled by a thermoelectric heat-pump known as a Peltier element. A light-sensitive receiver measures the intensity of the direct reflection. When the mirror is clean and dry, the intensity of the reflected light is at its maximum. Conversely, a cold mirror with water vapour condensed on its surface scatters the light, resulting in less directly reflected light and in reduced signal intensity. Using this received light signal as feedback in a closed loop control system, the mirror is cooled to the temperature at which the thickness of the condensed layer, detected through the intensity of the received light, remains constant. A condensate layer of constant thickness, with no further net increase or decrease in condensation, is in dynamic equilibrium with the gas flowing over the mirror surface. In this equilibrium condition, the dew or frost point temperature of the gas is determined by measuring the temperature of the mirror. This mirror temperature is physically linked to the corresponding vapour pressure via the saturation vapour pressure functions.

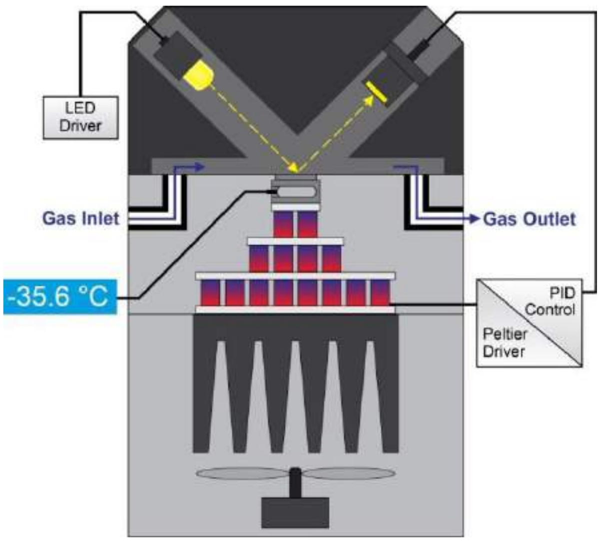


Figure 3-17: Dew point mirror

If the condensate is known to be in liquid form, even for temperatures below freezing, then the measured mirror temperature is taken as the dew point. If the condensate is known to be in a solid form as ice, then the measured mirror temperature is taken as the frost point. The measuring range of a chilled mirror in this application is limited by the condensation point of SF_6 which is about −65 °C at 100 kPa. This does not present a problem since the lowest expected frost point in a gas-filled compartment is generally above −60 °C frost point at 100 kPa, equivalent to about 10 ppmv. If measurements are taken at system pressures, the SF_6 condensation point is higher and can become a limiting factor in the measurement of the frost point temperature with a chilled mirror. Advanced chilled mirror hygrometers have the capability to properly distinguish between dew and frost by forcing all super-cooled water condensation into a solid state in the form of ice or frost. Once in this state, the condensed layer remains in a solid form and frost point temperature is accurately measured.

Instruments using Capacitive Polymer technology are the most commonly used hygrometers. These hygrometers usually measure the humidity at atmospheric pressure, with the inlet connected to the gas compartment being sampled. Depending on the instrument design, flow rates are maintained either automatically or by manual adjustment of a needle valve. When a measurement is started, polymer sensors begin with a high indication and dry down during measurement. As they dry down below some desired threshold limit, the measurement can be terminated and no additional time is required waiting for a stable indication. Polymer sensors measure relative humidity (RH) and recalculate to other units for indication. Because the conversion from RH to frost/dew point or ppm is a very non-linear function, there is a significant loss of resolution at low humidity. In addition, because of its temperature dependence, the RH value decreases if the temperature increases at stable absolute humidity (constant vapour pressure and constant frost/dew point). High temperatures and low humidity compound the resolution problem of RH measurement. The typical specified measuring range of a polymer sensor is limited by a maximum temperature difference (ΔT) of 80 K between the frost/dew point and the temperature. This results in a lower limit of −60 °C frost point (10 ppmv) at 20°C and −40 °C frost point (129 ppmv) at 40 °C at 100 kPa standard absolute pressure.

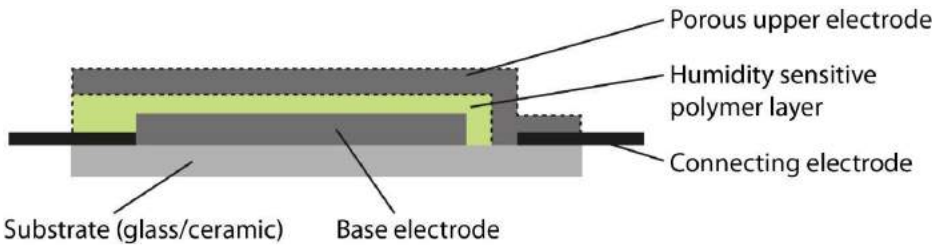


Figure 3-18: Structure of a polymer sensor

Aluminium Oxide technology is similar to the Capacitive Polymer technology. The sensor uses an oxide layer (Al_2O_3) allowing water molecules to migrate in and out of the porous structure changing the capacitance with water vapour content. Flow rates are maintained until the indicated reading stabilizes. Typical indications are in frost/dew point. Most Aluminium Oxide sensors are maintained dry within a desiccant chamber between measurements, and when not in use. This means that these instruments start with a dry indication and rise during the measurement process to a higher value. Since the aim is to remain below a specified threshold limit, it is difficult to determine when the instrument has reached its final stable value. Some Aluminium Oxide sensor instruments indicate dew point below 0 °C although frost point is the correct term.

Figure 3-19: Aluminum oxide sensor

DEGREE OF MATURITY

Chilled Mirror Method

Capacitive Polymer Method

Aluminum Oxide Method

EASE OF USE AND CONSTRAINTS

Humidity can be measured either via portable analysers or detector tubes, which can be connected to the filling tube, or modern sensors, which are permanently installed at the same place. The big advantage of permanent installed sensors is, that the components can stay in operation during the measuring and the values can be transmitted online to various monitoring systems.

3.3.4.3 Measurement of decomposition products

APPLICATION

GIS compartments which contain no switching elements should have no decomposition products at all and, therefore, if some are detected, intervention is warranted.

Compartments with switching elements can contain decomposition products that may have been generated by normal switching activity but also by abnormal arcing or sparking.

As decomposition products can influence the proper function of GIS compartments, they should be measured during regular maintenance activities.

MODE OF APPLICATION

Detector Tubes Method	**Periodic Measurement** ✔	Continuous Monitoring
Electrochemical Measuring Cells Method	**Periodic Measurement** ✔	Continuous Monitoring
Infrared Spectrography	**Periodic Measurement** ✔	Continuous Monitoring
Gas Chromatography	**Periodic Measurement** ✔	Continuous Monitoring

THEORETICAL BACKGROUND

There are different technologies available to measure the decomposition products. Detector Tubes make use of a chemical reaction in a special test tube, with the reaction identified by a change in colour. Such test tubes are available for different gases, such as SO_2, HF and oil mist. A defined quantity of measuring medium is fed through the test tube within a set period of time. The discolouration of the test tube scale indicates the gaseous decomposition product of the SF_6 present in quantitative terms. Tubes that are calibrated for SO_2 are also sensitive to other decomposition products like SOF_2 and SO_2F_2 etc. which can influence the reaction time to SO_2. Hence any measurement is an estimate of the decomposition product. The gas should be collected after flowing through the test tube either in a dedicated collecting vessel or flexible plastic bags, see Figure 3-20. Various measuring ranges are available and the measurement time varies from several seconds to minutes for the more sensitive ranges. No calibration is required but the expiration date of the test tubes must be observed. Typically 1–2 liters of gas are required for a measurement.

Figure 3-20: Detector tube and sampling arrangement

Electrochemical Measuring Cells are able to detect SO_2 and HF. An electrochemical sensor is based on an electrode system and an electrolyte calibrated to detect the substance being measured. The SO_2 or HF will react with the electrode changing its potential, which can be equated to a concentration in ppmv.

Infrared spectroscopy can be used to verify the quality of new gas, used gas and the cleaning and recycling process of contaminated SF_6. Infrared spectroscopy is a common type of spectroscopy used on a gas mixture for all decomposition products including the reactive substances i.e. HF, SF_4, SOF_4, SiF_4 and S_2F_{10}. It consists of an optical cell connected to a vacuum system. The result is a spectrum and the absorption of infrared light in the spectrum is directly proportional to the quantity of a component from low ppm values up to percentages. The measurement time for one sample is normally around 4 minutes for the complete measurement of the impurities and the main decomposition products. A non-dispersive infrared sensor (or NDIR) is a spectroscopic device often used as a gas detector. The main components are an infrared source, a sample chamber or light tube, a wavelength filter, and an infrared detector. The SF_6 gas is pumped into the sample chamber and gas concentration is measured electrooptically by its absorption at a specific wavelength in the infrared (IR) range. This technique enables NDIR sensors to achieve high level of selectivity. In terms of response time, an NDIR sensor typically takes one or more new readings every second. However, digital filtering, data processing, time needed to purge the sensor and flow enough gas to obtain a representative sample can increase the total measurement cycle to 3-5 minutes. [CIGRE_567_2014].

Gas chromatography is a common type of chromatography used on a gas mixture for separating and analysing compounds that can be vaporised without decomposition. It can be used to verify the quality of a new insulating gas, the integrity of in-service or used insulating gas. It is composed of a mobile phase (moving phase) – a carrier gas, usually an inert gas such as helium, and a stationary phase which is a microscopic layer of an inert solid support called a column. It is possible to have 2 or more columns in order to analyse different types of compounds. Each different compound requires a different time to traverse the column. The result is a chromatogram. The area of the peaks is proportional to the quantity of the component. In order to achieve a high degree of precision the instruments must be calibrated before use with reference gases for each substance intended to measure. Different columns coupled with different detectors can be used to analyse SF_6, N_2, O_2, CF_4, HF and oil mist, and the stable decomposition products.[CIGRE_567_2014].

DEGREE OF MATURITY

Detector Tubes

Electrochemical Measuring Cells

Infrared Spectrography

Gas Chromatography

EASE OF USE AND CONSTRAINTS

Identifying a threshold for the permissible level of decomposition products without a reduction of the dielectric performance of the gas is very complex and has proven to be impossible in practice.

Portable analysers are available in various numbers for on-site measurement. They can typically measure the decomposition products with Electrochemical Measuring Cells or Infrared spectroscopy.

Gas Chromatography usually is executed in laboratories. It is possible to use on-site portable Gas Chromatography having also a TCD (thermal conductivity detector) which can precisely measure the levels of Air, CF_4, SO_2, SOF_2 and SO_2F_2 in SF_6. However, a high levels of skill is required to operate these instruments and, therefore, they do not offer a practical option.

3.3.4.4 Measurement of SF_6 percentage

APPLICATION

From an equipment performance perspective, the most critical element is SF_6 content (clearly coupled with SF_6 density) and should be measured during regular maintenance activities as a consequence.

MODE OF APPLICATION

Periodic Measurement ✓	Continuous Monitoring

THEORETICAL BACKGROUND

There are different measuring technologies available. The measurement of the velocity of sound and the thermal conductivity in the measuring medium are usual. But recently there have been devices which are operated by measurement of condensation points.

The Sound Velocity works by evaluating the different sound velocities of gases. The sound velocity in nitrogen is normally around 337 m/s at 20° C and for SF_6 around 130 m/s at 20° C. The sound velocity measured in the measurement cell is temperature-compensated and is converted into the percentage SF_6 volume assuming that the mixture is composed only of SF_6 and nitrogen. Since the velocity of sound in oxygen is similar to that in nitrogen the results are applicable for an SF_6/air mixture. The accuracy of such devices is +/-1 % SF_6 content.

The same Condensation technique employed by a chilled mirror to measure the water vapour in SF_6 can be used to determine the purity of the SF_6 gas. Since the condensation point of pure SF_6 at a given pressure is a known value on the SF_6 vapour pressure curve, the %Vol SF_6 can be calculated based on the difference between the SF_6 partial pressure and the measured total pressure. This is a selective measuring method directly detecting the actual SF_6 content in a gas compartment, at 20° C. Thermal conductivity detectors (TCDs) continually measure the thermal conductivity of the SF_6 using the heated-filament method. The accuracy of TCDs is typically lower than those instruments based on sound velocity.

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

SF_6 percentage can be measured via portable analysers. Portable analysers are available in various numbers for on-site measurement.The test results are available immediatelly after the measurement, which takes approx. 2 minutes, dependent on the device type.

3.3.5 Oil Condition

3.3.5.1 Oil Condition

APPLICATION

Laboratory testing of oil has historically been used to determine the condition of equipment such as oil circuit breakers (OCB's) across all voltage levels. Information gained from this testing is used to detect if underlying faults exist or are developing and also to determine their severity. For bulk OCB's this can also assist in identifying ageing trends of the various components.

The oil tests can be divided in to three main categories; Dissolved gas-in-oil analysis (DGA), oil quality and particle analysis.

Failure modes for OCB's include electrical, mechanical and overheating. These failure modes can therefore be detected by using similar diagnostic techniques as used on transformers. There are two main types of OCB's, bulk oil and minimum oil. All tests can be performed on the oil from both types. However, for minimum oil circuit breakers, the most common tests are the oil quality set.

MODE OF APPLICATION

Bulk oil, Quality	**Periodic Measurement** ✔	Continuous Monitoring
Bulk oil, Metals	**Periodic Measurement** ✔	Continuous Monitoring
Bulk oil, DGA	**Periodic Measurement** ✔	**Continuous Monitoring** ✔
Minimum oil, Quality	**Periodic Measurement** ✔	Continuous Monitoring
Minimumoil, Metals	**Periodic Measurement** ✔	Continuous Monitoring
Minimum oil, DGA	**Periodic Measurement** ✔	Continuous Monitoring

For bulk oil circuit breakers samples can be taken with the equipment in-service, whereas for minimum oil circuit breakers, the equipment is generally required to be off-service. Sampling frequency can vary from yearly to bi-annual and even up to every 8/10 years depending on the maintenance policy of the company.

THEORETICAL BACKGROUND

Oil quality

Routine oil quality tests are most commonly referred to as being dielectric breakdown voltage, water content and acidity. Information gained from these three tests offer a good insight as to the overall condition of the oil. Dielectric breakdown voltage will provide information on the insulating capability of the oil. Water content will determine if the OCB has excessive amounts of water present. Since the majority of OCB's are free breathing, this is a common problem. Acidity will provide an indication of the extent of the degradation of the oil.

Particle analysis

The total number of particles can be used to detect abnormal quantities of by-products and wear materials. The ratio(s) of the size groupings provides information as to the extent a detrimental condition has progressed. Larger particles are especially important, as the dielectric strength of the insulating oil is more adversely affected by these particles, and formation of larger particles are an indicator of advanced deterioration. Particle typing has been used successfully in other fields such as lubrication and hydraulic systems for quite some time. In OCB's, particles are formed from three main mechanisms: wear, arcing and overheating.[Lewand2004]

Dissolved gas-in-oil analysis

During the operation of OCB's, gases are produced as the contacts separate. A prevalent gas is acetylene which can indicate normal or excessive arcing, hydrogen will also be associated with normal operation and are classified as arcing gases. As very little heating occurs in a healthy CB there should not be any significant amounts of gases such as ethylene, ethane and methane. Overheating of conductors and insulation can lead to a thermal condition which may cause surface carbonization, which can then lead to increased surface resistance and result in a thermal runaway scenario unless corrected. The ratio of heating to arcing gases should be consistent. Any change in these ratios can be used as an indicator of an abnormal condition developing.

DEGREE OF MATURITY

Bulk oil, Quality	■■■■■■□
Bulk oil, Metals	■■■■■■□
Bulk oil, DGA	■■■■■■□
Minimum oil, Quality	■■■■■■□
Minimum oil, Metals	■■■■■□□
Minimum oil, DGA	■■■■■□□

EASE OF USE AND CONSTRAINTS

For bulk oil circuit breakers the process of oil sampling is very much straight forward. Sampling ports are generally provided at accessible points without the need to remove the equipment from service.

For minimum oil circuit breakers the sample cannot be extracted without removing the equipment from service.

For both applications tests such as BDV, moisture content and neutralisation number can be performed on site using widely available portable test kits. The metal and DGA testing is most commonly performed in a laboratory environment.

3.3.6 Partial Discharge

A partial discharge (PD) in HV/MV switchgear is a localized dielectric breakdown due to a defect which causes local electrical stress concentration in the insulation medium. IEC 60270 standard defines PD as "localized electrical discharges that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor. PD are in general a consequence of local electrical stress concentrations in the insulation or on the surface of the insulation."

PD measurements provide important information about the health condition of the switchgear insulation. Traditionally PD tests have been used as quality assurance measurements during the production process of the switchgear in order to check for defects in insulation that could appear during the manufacturing process. Over the last 10-20 years they also started to be used for testing equipment in the field, which will be the focus of this section.

Some of the causes of PD in HV/MV switchgear are assembly error, free moving metallic particles, metallic protrusions or sharp edges fixed on the conductors, poor or loose electrical contacts, defects in solid insulators such as voids, cracks and metallic particles on insulator surface and contamination of the insulation medium.

Since PD activity causes progressive deterioration of insulating materials, the condition of the insulation should be monitored, preferably during the lifetime of the device. Because PD can increase the risk of insulation breakdown, early detection and location are important.

PD appears with various effects such as electromagnetic and acoustic (mechanical) waves, emission of light and chemical decomposition of the insulation medium. These physical and chemical effects can be detected by different diagnostic methods with sensors which are mainly classified as:

- Electrical methods
- Conventional methods according to IEC60270 (typically used for factory tests)
- Non-conventional electrical methods (typically used for field tests)
- Acoustic methods (typically used of field tests)
- Optical methods (typically used for field tests)
- Chemical methods

This section will focus on Electrical and Acoustic methods, both of which are widely used for switchgear testing.

The PD detection methods can be divided into conventional and non-conventional methods [Cho2011]. The conventional methods refer to the PD measurement procedures specified, i.e. by the international standard IEC60270, which requires the disconnection of power cables from the switchgear and testing offline with the specified test circuit. This can be avoided by using non-conventional methods that are non-intrusive and allow the PD detection without disconnecting the cables from the switchgear [Kornhuber2012]

PD measurements in HV GIS is very well accepted and is a mature measurement technique. In MV application it has started to be applied recently.

With this said, it should be stated that field PD testing could have false positive results due to large external noise or measurement disturbances outside the switchgear, as well as cross talk between phases. Therefore, for the interpretation of the results, it is necesary to have a PD expert or use a PD expert system. In addition, it is advisible that results are reviewed by the switchgear expert, in order to draw the relationship between the test results of non-conventional field tests and conventional tests in the factory. This practice should lower the probability of false positive results.

3.3.6.1 UHF method

APPLICATION

The UHF method was first developed in the late 80's for use in high voltage GIS, specially because GIS insulation was very sensitive to the presence of metallic particles. The detection of partial discharge by the UHF method made possible the detection and location of these metallic particles. Currently the UHF method is used not only in GIS but in MTS (Mixed Technology Switchgear) and also in power transformers and in MV equipment.

MODE OF APPLICATION

UHF Partial Discharge	**Periodic Measurement** ✔	**Continuous Monitoring** ✔

THEORETICAL BACKGROUND

PD appears as high frequency current pulses whose rise time can be shorter than 100 ps. The fast rise-time pulses provide a high frequency electromagnetic transient propagating inside the enclosure whose frequency contents can distribute above 2GHz. The PD detection method working in the UHF range, 300MHz to 3GHz, is called the UHF method. The propagation velocity of the UHF electromagnetic waves depends on the relative permittivity of the surrounding medium. For example, in oil insulation it is estimated about $2\cdot[10]^8$ m/s and is around $3\cdot[10]^8$ m/s in SF_6. The electromagnetic wave generated by PD can be detected by means of antennas internally and externally mounted on the apparatus. Sensors mainly used for the UHF method are:

- Internally mounted disc shaped sensors
- External window / barrier antennas

Figure 3-21: Internally mounted plate sensor installed on gas-insulated switchgear [Lopez-Roldan2013]

The internally mounted sensors are intrusive since they require HV/MV switchgear to be shutdown and opened up for installation. The UHF methods using external sensors are a non-intrusive diagnosis method.

DEGREE OF MATURITY:

UHF method

EASE OF USE AND CONSTRAINTS

The UHF method is a very well established technique and has proved to be a powerful method to detect partial discharges. The best case is if the GIS comes from the factory with UHF sensors already installed. In case of existing GIS without sensors, then it is required to have dielectric windows where external UHF sensors can be placed. If the GIS does not have any dielectric openings where the external sensors can be placed, it is then required to retrofit the GIS with internal sensors which is a very intrusive operation. Another constrain is difficuly to correlate UHF activity to absolute pC value for online monitoring systems.

3.3.6.2 HF/VHF method

APPLICATION

HF/VHF method might be used in GIS switchgear also, but it is much less popular than the UHF method.

An important application of this method is in cables and cable joints.

MODE OF APPLICATION

HF/VHF method	**Periodic Measurement** ✓	**Continuous Monitoring** ✓

THEORETICAL BACKGROUND

The frequency contents of electric PD signals in solid or air insulation can be lower than the UHF range and are measured in HF/VHF frequency ranges. Sensors mainly used to detect the HF and VHF signals are inductive and/or capacitive types. The sensors predominantly applied for PD detection in HF and VHF methods are "capacitors", "current transformers", "Rogowski coils", "film electrode", "transient earth voltage probes", "resistive couplers" and so on. [Bacega2012]

Figure 3-22: High frequency CT installed on the ground conductor of the 145kV SF_6 circuit breaker [Bacega2012]

DEGREE OF MATURITY

HF/VHF method

EASE OF USE AND CONSTRAINTS

The HF/VHF is a well established technique. The application of this method is generally non-intrusive. The sensors can be installed in existing equipment without outages. When this system is used in AIS, there is a problem in overcoming the influence of external noise and external PD in busbars, insulators etc.

3.3.6.3 TEV method

APPLICATION

The TEV method is mainly used in indoor metal enclosed MV switchgear. It can be also used in HV GIS.

MODE OF APPLICATION

TEV method

THEORETICAL BACKGROUND

The Transient Earth Voltage (TEV) method detects induced voltage spikes on the surface of the metal panel created by PD in HV/MV apparatus. When PD is initiated, current spikes are created in the conductor and the surrounding earthed metal structure. The TEV signals escape from electrical discontinuities of the metal structure and can be picked up with an externally mounted TEV probe sensor pick up. [Garnett2011, Davies2007]

It should be noted that by using the TEV method, PD activity can be recognized through any insulation material. Through the capacitive coupling between the high voltage component and the outer metallic surface, a part of this electromagnetic wave energy is transferred to the outer metallic surface through air, oil, and epoxy. [Boltze2011]

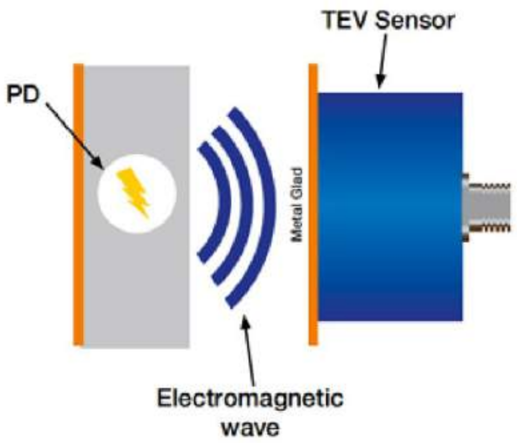


Figure 3-23: Principle of TEV sensor arrangement [Boltze2011]

DEGREE OF MATURITY:

TEV method ■■■■■■■

While TEV is a mature method on indoor metalclad and metal enclosed switchgear, there is an ongoing research on PD measurements on overhead solid dielectric switchgear utilizing a slight variation of TEV principle [Uzelac2015].

Figure 3-24: On-line PD measurement on 27kV solid dielectic insulation recloser [Uzelac2015]

EASE OF USE AND CONSTRAINTS

The TEV method is a well established technique. It is designed for use on indoor metalclad MV switchgear containing Epoxy, oil or air insulation. For higher voltages and for outdoor applications, the discharges from bushings and busbars above the switchgear could produce too much electrical noise and confuse the results. [Brown1996].

3.3.6.4 Acoustic method

APPLICATION

The acoustic method was initially developed to detect PD in transformers. It was then used in HV GIS and nowadays is also used in MV metal enclosed switchgear.

MODE OF APPLICATION

Acoustic method	**Periodic Measurement** ✓	**Continuous Monitoring** ✓

THEORETICAL BACKGROUND

PD appears as point source of acoustic wave (mechanical wave) in the ultra-sonic range. These acoustic waves spread through the internal structure of the apparatus and reach the external surface. The resulting signal will depend on the PD source and on the propagation path. Frequency ranges technically used for the detection are the ultra-sonic range from 10kHz to 300kHz and the audible range from 100Hz to 3kHz.

The acoustic waves are detected and converted into electric signals by means of "piezoelectric sensors", "structure-borne sound-resonance-sensors", "accelerometers", "opto-acoustic sensors" and "condenser microphones". Externally mounted sensors used for picking up the acoustic signals generated by PD in HV/MV apparatus are normally either accelerometers or acoustic emission sensors.

Accelerometers give an output signal proportional to the acceleration of the enclosure surface they are mounted on. Acoustic emission (AE) sensors give an output signal proportional to the velocity of the enclosure surface they are mounted on. The AE sensors operate in resonance.

The acoustic method is usually non-intrusive and mainly used for location of PD source.

DEGREE OF MATURITY

Acoustic method

EASE OF USE AND CONSTRAINTS

The acoustic method is a well established technique. It is condidered as complimentary to electrical PD detection and often used in combination with other methods such as the UHF in HV GIS or the TEV in MV switchgear. Because the sensors are attached to the grounded metal enclosure or a microphone is used, there is no need for an outage to install the sensors and perform the measurements.

The detection and analysis of acoustic waves generated by PD sources can be complex because the wave can be distorted due to numerous factors including division due to multiple pathways and transmission lossess in different media and at their interfaces. In addition, longitudinal and tranverse wave types travel at different velocities and suffer refections at impendance disontinituious [Dennis2006]. Therefore, a skilled oprerator is required for successful acoustic detection of PD.

3.3.7 Power Factor / Capacitance

3.3.7.1 Power Factor / Capacitance

APPLICATION

Power factor testing of circuit breakers is one way to assess the integrity of both the internal and external insulation. Test sets generally have an output of 10 kV and are portable in nature so that they can be used in all substation environments. This testing technique has historically been used on oil circuit breakers, however, there are also numerous white papers documenting the value of testing SF_6 filled switchgear. The test is commonly performed during scheduled maintenance and in most cases can be performed without the need to remove the high voltage conductors.

The purpose of the power factor tests is to detect the presence of contamination and/or deterioration of the breaker's insulating system, which will allow corrective actions to be taken to ensure the integrity of the breaker. This is done by measuring the insulation's dielectric-loss and capacitance and calculating the power factor. The increase of the dielectric-loss, and consequently the power factor, is representative of an increase in contamination and/or deterioration of the insulating system and can detect a number of problems including:

- Moisture contamination resulting from leaks or incomplete cleaning and drying
- Deterioration of line-to-ground and contact-grading capacitors
- Surface contamination of weather sheds
- Deterioration of insulating components such as operating rods, interrupters, interrupter supports caused by corrosive arc by-products.
- Impurities, contamination and/or particles within insulating medium

MODE OF APPLICATION

Power Factor	**Periodic Measurement** ✓	Continuous Monitoring

THEORETICAL BACKGROUND

The two most common circuit breaker types are dead tank and live tank. Figure 3-25 below shows the basic construction of a dead tank circuit breaker. The power factor tests are performed with a number of different connections and also with the circuit breaker in both the open and closed position. When the circuit breaker is in the closed position, all support insulators will be included in the measurement.

For dead tank circuit breakers the following components will be included in the test circuit:

- Bushings & tank
- Insulating medium
- Guide assembly
- Interrupter
- Operating rod
- Support insulators

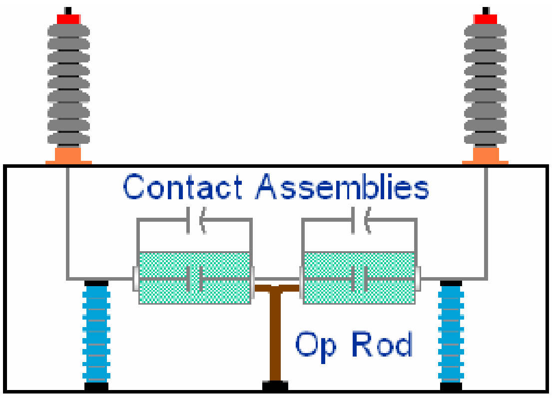


Figure 3-25: Dead tank circuit breaker

For a live tank circuit breaker as shown in Figure 3-26 the following components will be included in the test circuit:

- Interrupting & support chamber insulators
- Insulating medium
- Interrupter
- Operating rod

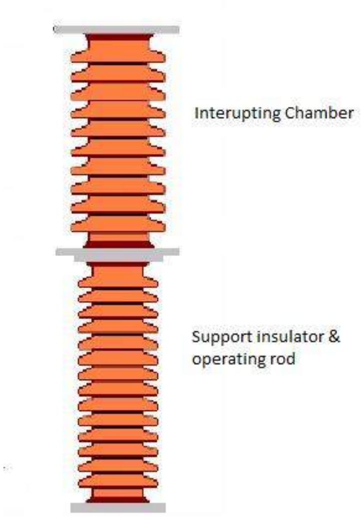


Figure 3-26: Live tank circuit breaker

Measurements of support insulators and interrupter assemblies that are not in parallel with grading capacitors are evaluated on the basis of current and watts. If the interrupter assembly includes a contact grading capacitor, the evaluation is based primarily on the measured capacitance and calculated power factor.

DEGREE OF MATURITY

Power Factor

EASE OF USE AND CONSTRAINTS

Power factor testing of circuit breakers is a well-established test technique. The tests are minimally intrusive due to the fact the apparatus needs to be isolated from the network. Depending on how the circuit breaker is connected to the substation there may be a need to remove some high voltage conductors in order to isolate it from other substation components.

Generally, test results are analysed on the basis of measured current and power loss. If the test includes a measurement of a grading or line-to-ground capacitor, power factor and capacitance should also be evaluated. Changes in any of these parameters would warrant concern. Usually, insulation problems are reflected in an increase in the watts or power factor and either an increase or decrease in the measured capacitance.

Results should be compared with data from similar breakers tested. Comparison should also be made with initial and previous test data.

3.3.8 Radiographic

3.3.8.1 X-Ray

APPLICATION

Radiographic inspection is a method for inspecting the internals of a switchgear without disassembly and is typically performed on HV GIS. Radiography requires an X-ray source, an image plate, and computer equipment to digitize the image. Figure 3-27 shows a typical placement of the radiographic equipment during imaging.

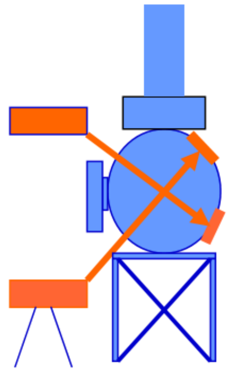


Figure 3-27: Example placement of X-ray source and image plates. [Stadelmeier2006]

The X-ray image can be analyzed visually to find problems in either wear or manufacturing defects of the switchgear. The images can be compared to previous images or manufacturer schematics to determine if there is a problem. Figure 3-28 illustrates the use of X-ray images to identify a defect.

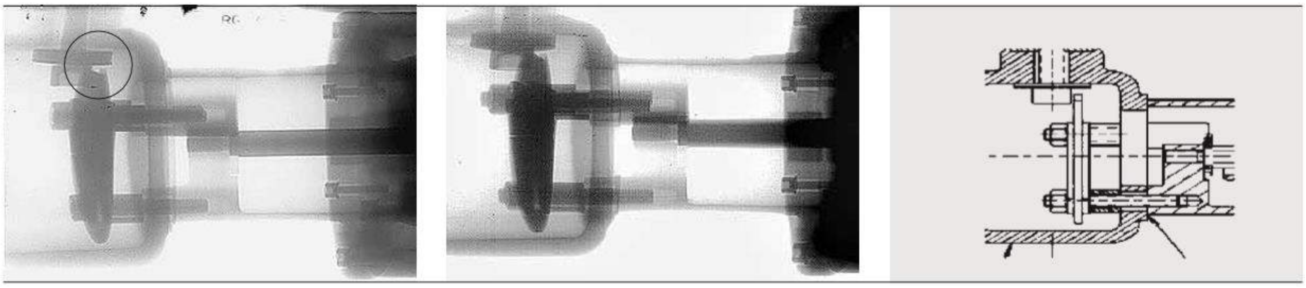


Figure 3-28: X-ray images of an incorrectly inserted bolt. Left: There is a gap between the disk and casing. Middle: proper installation. Right: manufacturer's schematic [Michaelson2012]

MODE OF APPLICATION

Periodic Measurement ✔	Continuous Monitoring

THEORETICAL BACKGROUND

Radiographic inspection is a very mature technology to look for defects in materials or equipment by placing a radioactive source on one side of the target and a screen on the other. Different materials will allow a different amount of the electromagnetic radiation to pass through them. These differences are exposed on the screen and then turned into an image. Depending on the material under inspection, the exposure time will vary, but is typically between 4 and 11 minutes.

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

The advantage of radiographic inspection is that it allows for visual inspection of the internal mechanisms of the circuit breaker without needing to disassemble the circuit breaker. This greatly reduces the amount of outage time required to perform the inspection (see Figure 3-29). Radiography can detect nozzle wear as well as manufacturing defects. For an effective use of the method, a very good knowledge of the interrupting chamber is needed together with expertise in X ray evaluation.

Circuit breaker type	Outage times	
	Traditional invasive internal inspection	Radiography
38 – 145 kV	2 days	2 hours
242 kV	3 days	3 hours
362 kV	4 days	3 hours
550 kV	5 days	4 hours

Figure 3-29: Comparison of outage times between an invasive internal inspection and radiography. [Michaelson2012]

Radiography does require the switchgear to be taken out of service during the inspection. When the contacts are engaged, there is not enough resolution to accurately assess their health through the X-ray image.

3.3.9 Resistance of Insulation

3.3.9.1 Insulation resistance Measurement

APPLICATION

Insulation resistance measurement is used for routine tests and as part of maintenance or overhaul activities. Also it is applied before and after potentially destructive insulation system testing – testing with rated or above rated operating voltage. The acceptable result is a condition for further testing using other methods. An insulation resistance measurement is performed after a high potentional insulation test as confirmation that no damage during the test occurred.

MODE OF APPLICATION

Periodic Measurement ✔	Continuous Monitoring

THEORETICAL BACKGROUND

The insulation resistance test is a spot insulation test which is based on Ohm's Law. DC voltage (typically 250Vdc, 500Vdc or 1,000Vdc for low voltage equipment <600V and 2,500Vdc and 5,000Vdc for high voltage equipment) is applied, the current flowing is measured and then the value of the resistance is simply calculated. In principle, the value of the insulation resistance is very high but not infinite, so by measuring the low current flowing, the ohmmeter indicates the insulation resistance value, providing a result in kΩ, MΩ or GΩ. This resistance indicates the quality of the insulation, where the higher the resistance, the better the condition of the insulation.

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

The insulation resistance test is a quick and simple test which provides a rapid indicator of insulation condition. It indicates serious degradation or contamination of insulation. Test objects should be out of service and completely discharged to the ground. Readings are altered by changes in temperature and presence of moisture. Also, too high applied voltage could lead to insulation degradation.

3.3.10 Transient Electromagnetic Emissions

During a CB switching operation, transient electromagnetic emissions (TEE) are generated by the electric discharges in each interrupter. The TEEs due to disruptive discharges in a CB such as prestrikes, re-ignitions and restrikes have a high-amplitude and a broadband frequency range.

Diagnosis of CBs by TEEs is an emerging method, entirely non-intrusive and in-service, very effective for detection and analysis of re-ignitions and restrikes in the interrupter during opening operations and for precise prestrike monitoring during closing operations [Poirier2014, Lopez-Roldan2014, Yoshida2016]. It also allows, in some conditions, the evaluation of arc duration for a live-tank CB.

Three distinct diagnostic methods have been developed concurrently with different degrees of maturity and targeting different types of CB:

- TEE detection with UHF antennas
- TEE detection with capacitive sensors
- TEE detection with PD couplers

All these methods can be applied for both HV and MV CBs.

MODE OF APPLICATION

The more appropriate application mode of the three above-mentioned diagnostic methods is periodic measurement.

MODE OF APPLICATION	**Periodic Measurement** ✔	Continuous Monitoring

3.3.10.1 TEE detection with UHF antennas

APPLICATION

The method of TEE detection with UHF antennas uses four passive UHF antennas (Figure 3-30). Its principle is based on location by triangulation of the source of emission allowing the per interrupter analysis of live-tank CBs [Poirier2010, Poirier2014] and per pole analysis of dead-tank CBs. The data acquisition is completed by measurement of line currents and opening and closing coil currents. The latter is also used to trigger the signal acquisition.

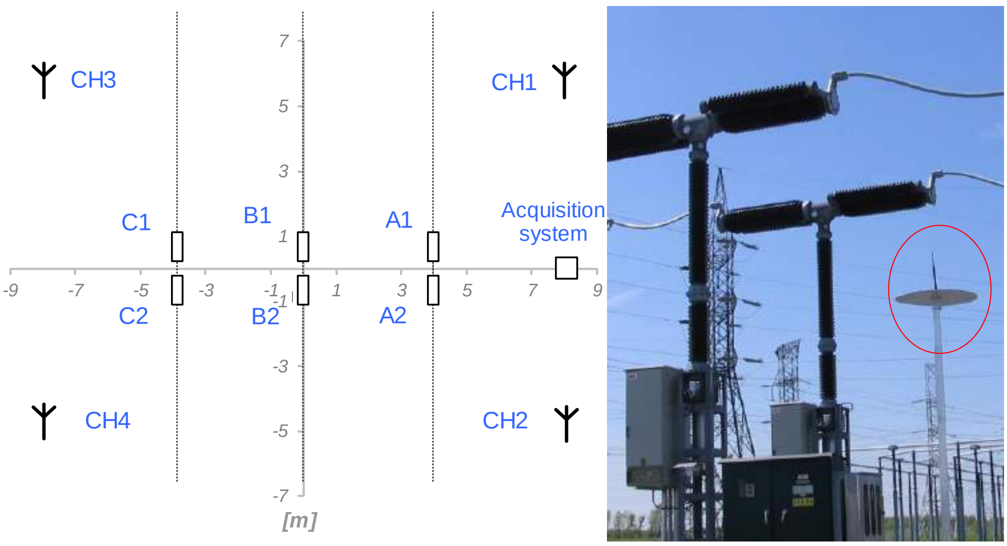


Figure 3-30: Measurement setup with four antennas installed around a 230 kV SF_6 CB; antennas positions are marked by CH1, CH2, CH3 and CH4 and interrupters by A1, A2, B1, B2, C1 and C2 [Lopez-Roldan2014].

THEORETICAL BACKGROUND

The TEE related to the disruptive discharges in CB measured by four UHF antennas shows a dominant frequency around 300 MHz, and has very short duration of less than one microsecond. It is measured in time domain using an acquisition system with at least 1 GS/s sampling rate. The location by triangulation uses time difference of arrival (Figure 3-31) [Poirier2010, Poirier2014, Lopez-Roldan2014].

Currently, only the occurrence time of TEE and location of emitting interrupter are used for analysis.

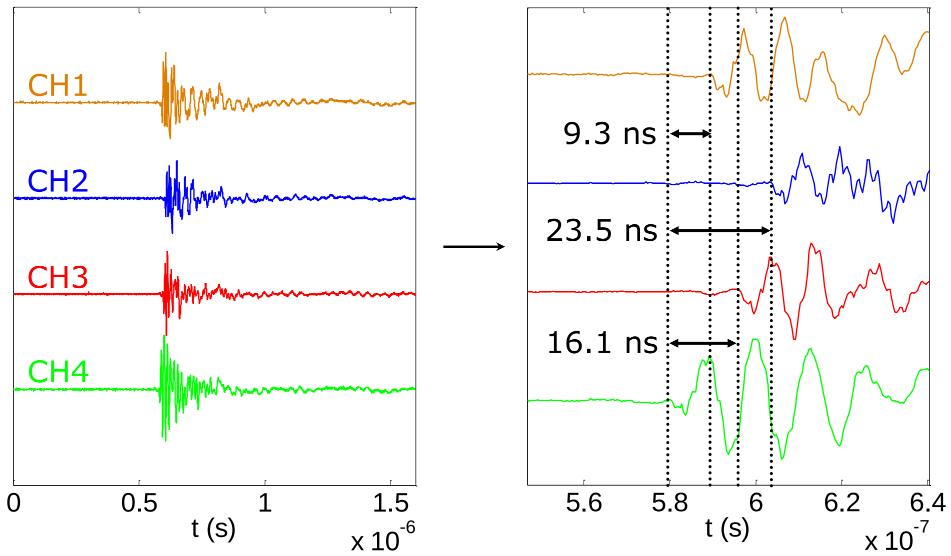


Figure 3-31: TEE recorded by four antennas and evaluation of time differences of arrival required for location of the interrupter [Lopez-Roldan2014]

Measurement of TEEs allows a precise and direct evaluation of basic parameters such as: occurrence and location of re-ignitions and restrikes in the interrupter, arc duration in each pole on opening as well as prestrike monitoring in each interrupter on closing. Combined analysis of these basic parameters allows evaluation of indicators related to the CB condition for which an overview is provided in Table 3-2.

Table 3-2: Overview of basic parameters and condition indicators for TEE method

	Opening/ closing	Measured Basic Parameter	Condition indicator
1	O	re-ignitions per interrupter	re-ignitions rate over several operations
2	O	restrikes per interrupter	restrikes rate over several operations
4	O	arc initiation and arc extinction per pole	opening time and arcing time (IEC 62271-100)
4	O	arc duration per pole	sampling of I^2T over the measurement period
8	C	instant of current making (pre-arc in every interrupter)	make time per pole (IEC 62271-100)
5	C	prestrike per interrupter	prestrike delays between interrupters; multiple prestrikes occurrence
9	C	prestrike per interrupter related to making current	advanced supervision of controlled switching [Portales2015]

DEGREE OF MATURITY

The system is tested in the field. Preindustrial prototype is available and is used on a regular basis at least in one utility. Many case studies are reported [Portales2015], [Doche2017].

TEE detection with UHF antennas

EASE OF USE AND CONSTRAINTS

The measuring system is installed and used while the CB operates normally and is installed for a limited period of time (few months) which allows recording of a sufficient number of CB operations for statistical analysis.

The installation and utilization are entirely non-intrusive. Clip-on current clamps need to be installed on opening and closing coil conductor and, optionally, in the secondary circuit of current transformer.

3.3.10.2 TEE detection with with capacitive sensors

APPLICATION

The TEE detection with the capacitive sensors method is more suited for dead-tank CBs. It uses an active high-frequency antenna (AA) placed in the vicinity of the CB and three broadband passive antennas (PA), acting as capacitive sensors of electric field, placed under each phase conductor (Figure 3-32). Its astuteness relies on the analysis of voltage image waveforms allowing per pole investigation [Lopez-Roldan2007, Lopez-Roldan2012].

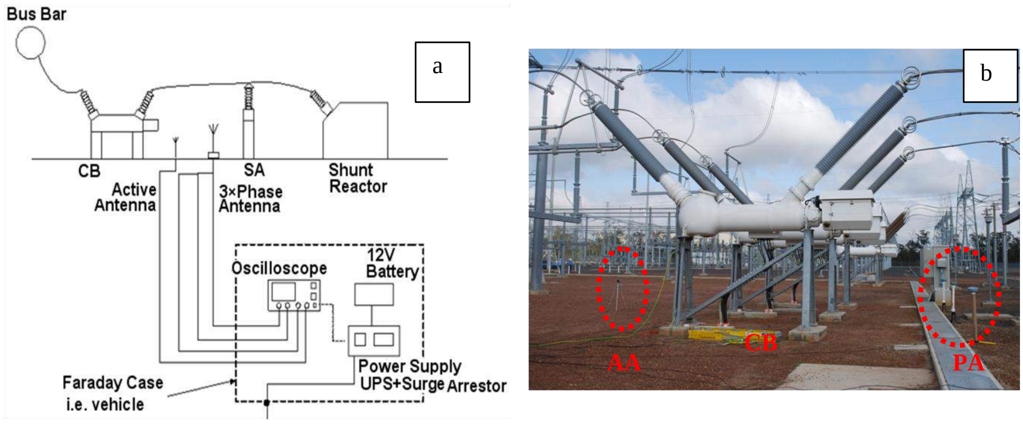


Figure 3-32: Measurement setup with three PAs and one AA: (a) general test arrangement and (b) positioning of AA and three PAs next to a 275-kV dead tank CB [Lopez-Roldan2014].

THEORETICAL BACKGROUND

The TEEs related to the disruptive discharges in dead-tank CB are attenuated by the tank and its bushings but they can be measured with AA. On the other hand the voltage perturbation is propagated on three phase conductors and can be captured by capacitive sensors (PA) (Figure 3-33). The analysis of amplitude of PA recordings allows determining on which pole the discharge occurred. The signal of AA is used to trigger the signal acquisition.

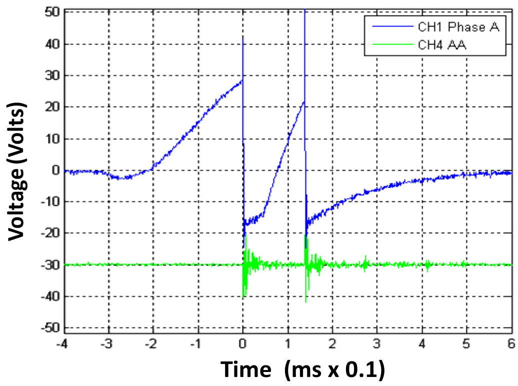


Figure 3-33: Double re-ignition in phase A recorded by AA (green) and PA (blue) [Lopez-Roldan2014]

DEGREE OF MATURITY

This method was successfully demonstrated in-field using an experimental prototype.

TEE detection with capacitive sensors

EASE OF USE AND CONSTRAINTS

The deployment of AA and PA is completely non-intrusive; there is no interaction with the CB. Interpretation of measurement may not be straightforward because of possible crosstalk between the antennas and phase conductors.

3.3.10.3 TEE detection with with PD couplers

APPLICATION

The TEE detection with UHF antennas method can be extended to dead-tank CB with two interrupters in series using the high sensitivity antennas i.e. partial discharge (PD) couplers. The location of the pole is based on the time difference of arrival of an EM wave (section 3.3.10.1) the detection of the interrupter is based on the earliest rising edge of EM wave within the pole [Yoshida2016].

THEORETICAL BACKGROUND

This method assumes that the TEE wave propagates in the metallic enclosure (GIS or dead-tank CB) at the speed of light in two directions and is radiated by bushings on each side. Using at least two PD couplers, the time difference between the earliest and second rising edge allows the determination of the interrupter in which the discharge occurred.

DEGREE OF MATURITY

This method is presented as a R&D concept.

TEE detection with PD couplers

EASE OF USE AND CONSTRAINTS

The installation of antennas is non-intrusive. However, this method is at the R&D stage and there is no evidence that the interrupter identification is feasible. It should be noted that transient EM waves generated by disruptive discharge will propagate inside the CB and will be emitted by the bushings almost simultaneously making the determination of the earliest rising edge difficult.

3.3.11 Temperature

Temperature changes (excluding environmental factors) can be a leading indicator of a developing issue with the conductors of switchgear, such as poor contact. Measuring the temperature of the conductors for MV and HV switchgear is challenging because the sensors need to make the measurement and transmit the results while being isolated from the high voltage on the conductors. The following methods are different ways to approach this problem.

3.3.11.1 Infrared (IR) Cameras

APPLICATION

The use of infrared cameras to perform thermal scans of switchgear has been a common practice.

MODE OF APPLICATION	**Periodic Measurement** ✓	Continuous Monitoring

To conduct a survey with an infrared camera, the switchgear must have an IR window (see Figure 3-34) installed in a location that has line of sight access to the conductors. The thermographer will open the viewing window, take a thermal picture of the conductors and document the results.

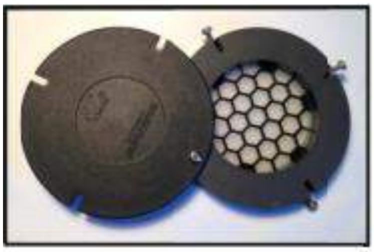


Figure 3-34: IR window [Durocher2015]

THEORETICAL BACKGROUND

Infrared energy is radiated from objects proportional to their temperature. The wavelength of IR radiation is longer than that of visible light. The sensors in IR cameras are designed specifically to capture these longer wavelengths and correlate the image data into temperature values. Accurate conversion of the IR radiation values into the absolute temperature of the object´s surface is dependent on the being able to know properties such as the emissivity of object, window transmission, etc. [Jadin2012].

DEGREE OF MATURITY

Use of the IR cameras with and without IR windows is standard practice in the field. Test equipment is commercially available.

Infrared (IR) Cameras ■■■■■■■

EASE OF USE AND CONSTRAINTS

The application of IR cameras for thermal scans is straight forward and understood. That said there are constraints with this technique. One of the constraints is that this technique does not lend itself to continuous monitor applications due to the cost of the IR camera technology. [Lindquist2011] There are some advances in lower cost IR sensors which may alleviate this problem in the future. Another constraint is the fact that the cameras must have line of sight to the target surface. Design and construction of modern MV and HV switchgear prevents visual access to some major components which should be monitored [Durocher2015].

3.3.11.2 Fiber Guided IR Temperature Sensors

APPLICATION

Fiber guided IR sensors operate on a similar theory as IR cameras (detection of radiated infrared energy) however they are more practical for continuous installation in the application. As the measurement is optical it provides the required isolation levels. The technology is particularly useful in applications where line of sight is not possible with an IR camera (i.e. inside spouts) or online monitoring is required. The IR sensor can be mounted in the high voltage area of the switchgear and uses an optical fiber to transfer the IR radiated waves to an IR detector in a low voltage cabinet. Figure 3-35 below shows a typical installation.

Figure 3-35: Fiber guided IR sensor mounted to the contact arm

MODE OF APPLICATION

Periodic Measurement	**Continuous Monitoring** ✔

THEORETICAL BACKGROUND

These sensors operate on the same theory as IR cameras. They detect the amount of IR emitted from the surface of an object and convert that to temperature [Livshitz2005].

DEGREE OF MATURITY

Various designs of these types of sensors have been successfully installed and used by at several major OEM on their CB's.

Fiber Guided IR Temperature Sensors 

EASE OF USE AND CONSTRAINTS

The method is rather costly as the fibers have to have low losses in the IR range and the detector could be GaAs or InGaAs PIN photodiode. The cost of the measurement system can be prohibitive in certain applications. The application of these sensors could be challenging due to the mechanical shock and vibration during the CB operation [Wildermuth2014a].

3.3.11.3 Surface Acoustic Wave

APPLICATION

Surface Acoustic Wave (SAW) systems consist of a passive temperature sensing element that, when interrogated via a wireless signal, returns a signal proportional to the temperature of the surface upon which it is mounted. Figure 3-36 illustrates the components of a SAW-based measurement system [Sengenuity2013]. This measurement technique can be used in both MV and HV switchgear.

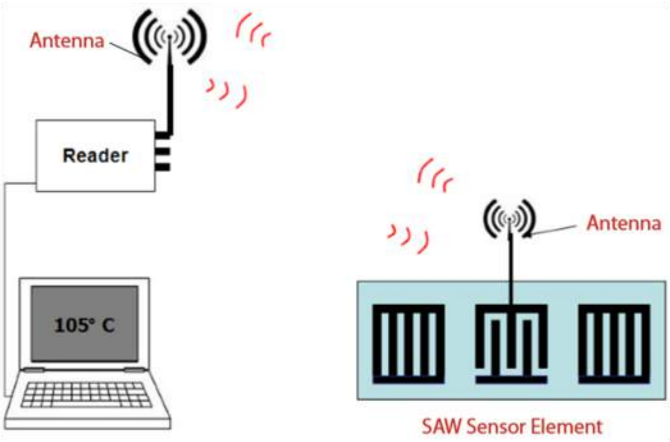


Figure 3-36: Wireless SAW-based temperature measurement system [Sengenuity2013]

MODE OF APPLICATION

Periodic Measurement	**Continuous Monitoring** ✓

The installation of a SAW based measurement system requires the switchgear being removed from service as access to the high voltage compartment is necessary for the mounting of the sensors and antenna.

THEORETICAL BACKGROUND

SAW sensors are based on displacement waves of atoms in single-crystal solids, whereby the wave is a combination of longitudinal and transverse, and limited to the atom layers near the surface of the solid. The waves used in acoustic wave devices are converted from and to electric signals piezoelectrically using metal structures called interdigital transducers (IDTs), deposited on top of the crystal in a production process similar to that of semiconductor devices. Therefore, piezoelectric crystals must be used for SAW devices. The most common choices include various cuts of quartz ($SiO2$) or lithium tantalate ($LiTaO3$). While SAWs using these materials can function only up to about 200°C, high-temperature SAW materials stable up to 750°C or more are under development.

SAW devices allow only specific wavelengths to pass, depending on material, crystal cut and IDT structure, forming efficient bandpass filters. Surface acoustic waves generated at an interdigital transducer travel along the surface of the crystal until the end of the crystal (Piezo Substrate) or until they reach a reflector, where they may be fully or partially reflected, until they reach an IDT, where they are converted back into an electrical signal. As purely passive devices, SAW sensors are well suited for wireless readout, as the IDT can be directly connected to a suitable antenna used for both receiving the signal and sending back the response without any electronics or energy source on the sensor.

DEGREE OF MATURITY

Though the sensing technology is mature and commercially available, the difficulties of the method lie in wireless signal transmission.

Surface Acoustic Wave 

EASE OF USE AND CONSTRAINTS

SAW based systems offer a wireless and passively powered option for monitoring temperature at discreet points in switchgear. Some of the challenges with these systems involve the complications of wireless communications in an inherently electromagnetically noisy environment. The placement and shielding of the sensors and antennas should be carefully considered before deploying. Further the number of sensors can be limited in the frequency band to be used.

3.3.11.4 Wireless Temperature Sensors

APPLICATION

There are several options for wireless temperature sensing other than SAW based systems. The primary difference between these sensors are the specifc wireless communication protocol used and the functionality enabled by that protocol. A typical wireless system consists of a reader and sensors (see Figure 3-37 below). The reader is a device with a data processing module and antenna for generating the electromagnetic field to interrogate the sensor. The sensor is a device consisting of an antenna, a chip for management of communication and identification, a probe for measuring the temperature, and an enclosure. RFID and Zigbee are examples of the types of wireless protocols used with temperature sensors. Each protocol has its own advantages and disadvantages in regards to the range, number of sensors on a single network, frequency band regulation and power source. These sensors can be used in both HV and MV switchgear.

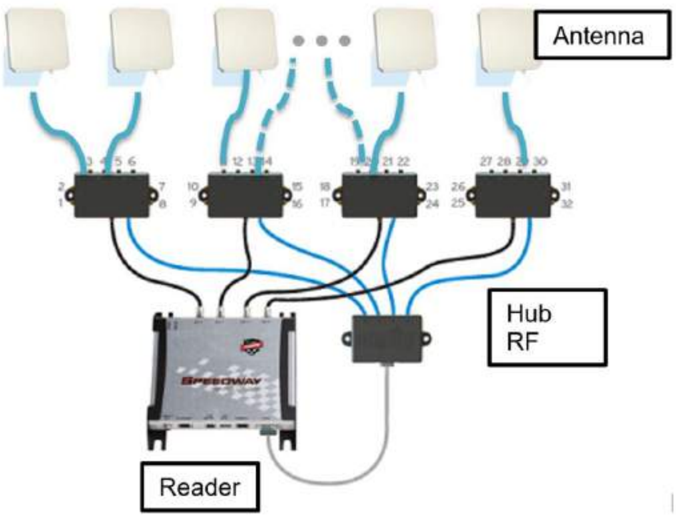


Figure 3-37: Complex UHF RFID system to monitor a complete MV switchboard

MODE OF APPLICATION

Periodic Measurement	**Continuous Monitoring** ✔

The installation of wireless temperature sensors requires that the switchgear is out of service. Once the sensors are installed, there is no need to perform regular maintenance on the measurement system. Figure 3-38 shows an example of a Zigbee sensor.

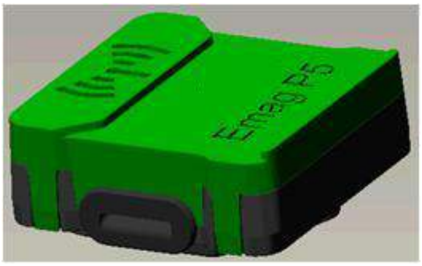


Figure 3-38: ZigBee thermal sensor with energy harvesting

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

The use of wireless based sensors allows for a non-intrusive method to continuously measure temperature within a switchgear. RFID base sensors have the advantage that they can be passively powered and do not require any kind of energy harvesting. RFID has limitations related to the range (typically 50cm between the sensor and reader) and the regional regulations on its frequency band. Conversely, Zigbee requires the sensor to be actively powered, but operates on a frequency band (2400-2500 MHz) which is open and unified worldwide. Zigbee sensors can harvest their energy from the temperature rise in the conductor or directly from the main circuit. Powering the sensor directly from the main circuit is simpler and also greatly increases the sensor's wireless range which reduces over complexity in the overall Zigbee network.

3.3.12 Timing

Coordinated operation of mechanical and electromechanical components is critical for proper performance of the circuit breaker. Monitoring for proper sequencing and timing of these systems can reveal potential conditions that might lead to improper performance. There are several methods associated with the timing of components during operation of the circuit breaker.

3.3.12.1 Timing of main breaker contacts

APPLICATION

Timing tests are used to determine the time for open (trip), close, close-open and reclosing operations. These times are essential for the safe and reliable circuit breaker operation and, therefore, the result of a proper circuit breaker design. The main contact times are checked after production, commissioning and in service during periodic maintenance. To do so, the timing test devices have to be connected to the coils and to the main contacts. For instance see Figure 3-39.

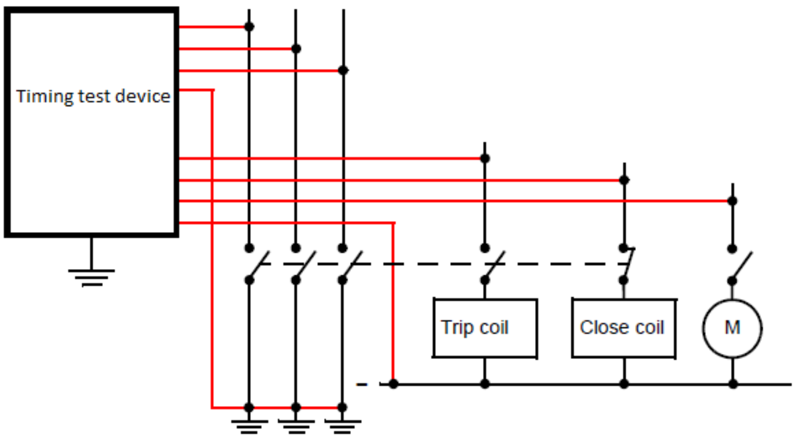


Figure 3-39: Timing test device setup [OMICRON2017]

MODE OF APPLICATION	**Periodic Measurement** ✔	Continuous Monitoring

THEORETICAL BACKGROUND

Standards [IEEE1999] and [IEC2008] define the operation time as the time from energizing the coil until the main contacts are opened or closed. A regular timing test device supplies a voltage to the coils and uses an internal clock to measure the time until the main contact state has changed. To detect that state change, basically two methods are usually used:

- Voltage divider method; Measures voltage change
- Resistance threshold method; Measures resistance change

These methods are not applicable when both sides of the circuit breaker are grounded (for example, GIS), because the signal change is not detectable [Weuffel2016]. There are alternative test methods available:

- Dynamic capacitance measurement (DCM)

- Current sensor measurement (CSM)

DEGREE OF MATURITY ■■■■■■■

EASE OF USE AND CONSTRAINTS

To use timing test devices, the correct connections to the coils have to be known and the appropriate grounding techniques have to be considered to connect the device to the primary contacts of the circuit breaker.

3.3.12.2 Circuit Breaker Timing with Protective Relays

APPLICATION

This method is using the microprocessor-based relay already connected to the circuit breaker to protect the transmission or distribution feeders.

The method was developed and used by at least one of the US-based utilities to monitor the operation of 69kV OCBs with persistent slow trip issues. It allowed improving the maintenance planning and increasing the reliability of the existing equipment.

It should be noted that a similar algorithm is being successfully applied in the field of modern digital protection relays (see also section 3.3.3.2).

MODE OF APPLICATION

Periodic Measurement ✔	Continuous Monitoring

THEORETICAL BACKGROUND

This method is based on the unique capability of modern microprocessor-based relays to receive, process and analyze signals from multiple inputs and send alarms based on predetermined thresholds.

The relay combines the information received from:

- Trip Coil Monitor (TCM) feature of the relay associated with the existing circuit breaker;
- Normally open auxiliary contact of the circuit breaker (52a)
- Phase sensing elements of the relay

The signals are processed using a simple algorithm (see example presented on Figure 3-40) to identify slow operation of the breakers.

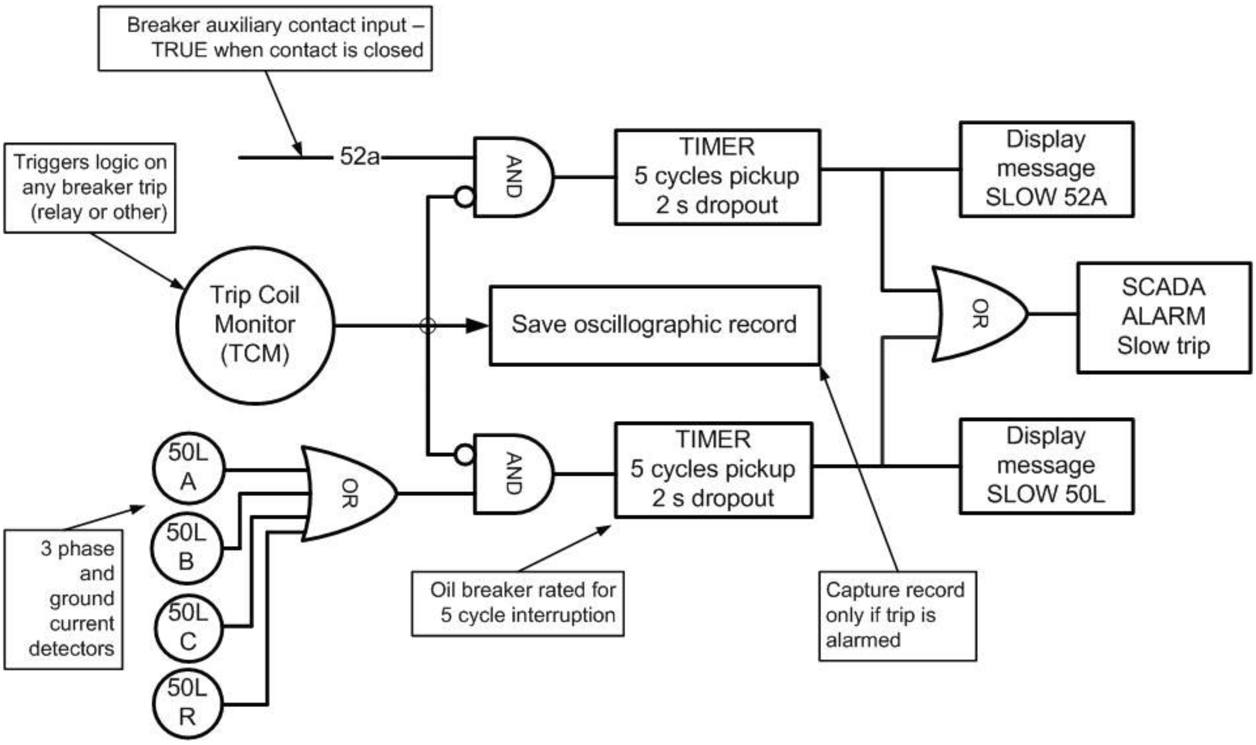


Figure 3-40: Relay programming for circuit breaker trip timing [Desai2012]

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

The biggest benefit of this method is that it allows the user to continuously monitor the circuit breaker opening times and report any deficiencies to the system operator using existing remote control infrastructure of the utility. This method could also allow detecting slow first trip operation of a circuit breaker after it was standing idle for month or even years in service. The first trip opening time can be slower than required for the proper interruption performance due to issues with lubrication, bearings, mechanical linkages, etc.

The disadvantage of this method is that the relay cannot track mechanical behavior of the circuit breaker components and observes only the timing of trip operation. Maintenance personnel would still have to perform the troubleshooting on the circuit breaker to identify and address the root cause of the slow operation. It should also be noted that some protective relay experts are not comfortable with the addition of programming that is not performing the protective tasks.

3.3.12.3 Circuit Breaker First Trip Analyzer

APPLICATION

This method is using specially designed and built test equipment to record the time between the application of the open or close signal applied to the circuit breaker and current in the current transformers connected on the primary circuit. It is widely applied by utilities to verify the condition of the operating mechanism and introduce condition base maintenance programs that allow to improve the reliability of the assets (circuit breakers) while reducing the maintenance cost. This method can be used on medium- and high-voltage equipment.

MODE OF APPLICATION

Periodic Measurement	✓	Continuous Monitoring

THEORETICAL BACKGROUND

The connection of the CB Analyzer is shown on the Figure 3-41.

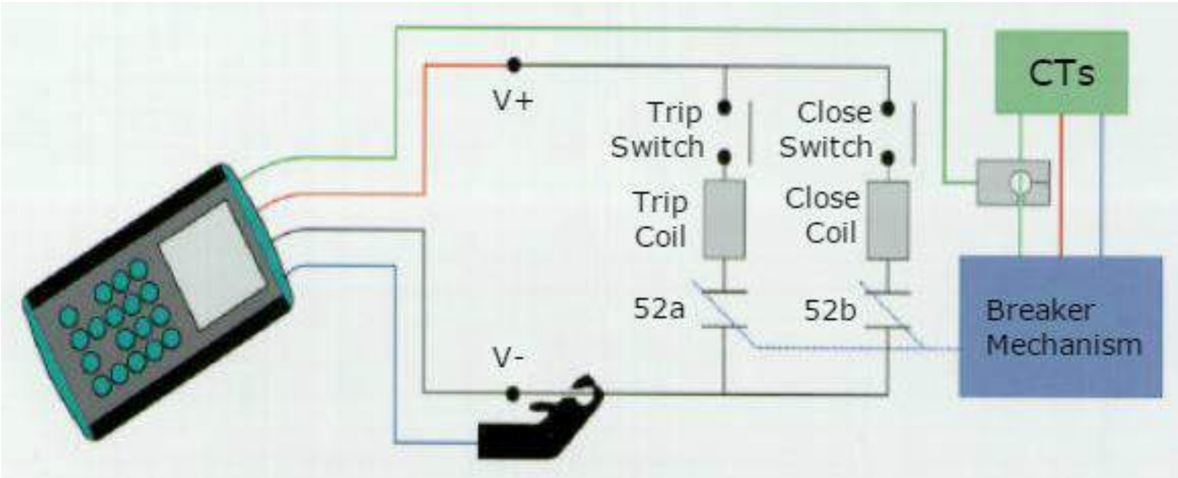


Figure 3-41: Connection of circuit breaker analyzer [Speed2000]

The operator would connect the analyzer when the breaker is in service. The trip (or close) signal to the circuit breaker would trigger the recording event. A clamp on the current transformer monitors the current in the primary circuit. The distinct distortion of the current waveform (see Figure 3-42) associated with the beginning of the arcing event would define the measured time interval of the circuit breaker operation.

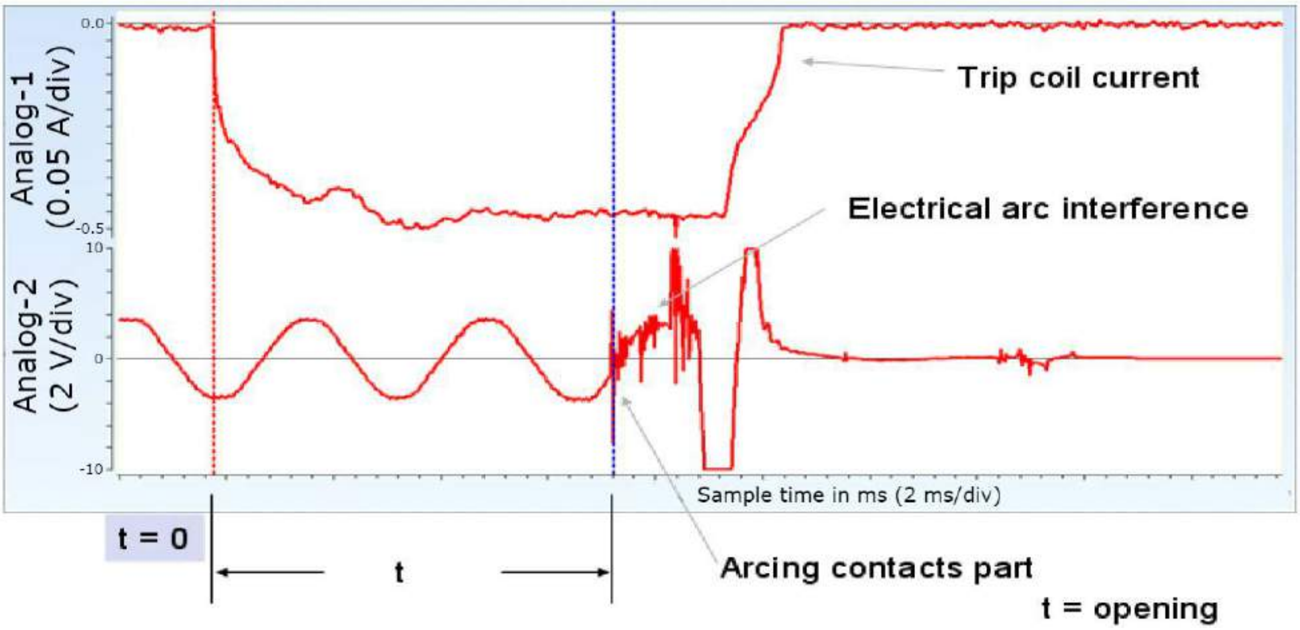


Figure 3-42: Opening time during first trip [Levi2010]

The information from the analyzer can be downloaded into a PC for future evaluation or could be reviewed immediately on screen.

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

There are several case studies conducted by US-based utilities that demonstrate the successful implementation of the First Trip Analyzers to identify circuit breakers that require maintenance. The collected information could also be used to develop a database to support the evaluation of the circuit breakers performance and implement a condition based maintenance program. In addition to recording the First Trip Time, the modern Analyzers can also provide valuable information on the trip coil current signature that could be used to check the condition of the mechanism and linkages.

This method does not provide any information on the contacts travel nor speed after the separation of the contacts during the opening cycle or before contact making during the closing operation. This could be considered as a disadvantage of the method.

3.3.13 Vacuum Condition

A detailed discussion of potential vacuum failure modes for VI's, when these modes could occur and the ultimate pressure level from these modes is given in [Taylor2014]. Vacuum interrupters (VI's) are the primary circuit interruption medium for medium voltage power systems, and increasingly are also used in low and high voltage systems. The VI performance requires that the pressure inside the VI be maintained below 10^{-3} hPa (1 hPa = 100 Pa = 0.75 torr) [Slade2007a]. VI's are tested to have an internal pressure $\leq 10^{-6}$ hPa before leaving the factory [Slade2007].

The performance of the VI is connected to the vacuum level, however its performance is not simply proportional to the pressure [Slade2007a]. Instead, the pressure inside the VI is best considered by putting the pressure into three groups. The pressure can be grouped by low pressure with $p < 10^{-3}$ hPa, mid-range pressure from $p \sim 10^{-3}$ hPa to the Paschen minimum pressure, and finally a high pressure. High pressures generally only occur if the VI will ultimately go up-to-air [Taylor2014]. In the low pressure range the VI will continue to function. In the mid-range the dielectric and interruption performance will be degraded, as also in the up-to-air range. OneA point to note with the dielectric performance is that it is lowest in the mid-range pressure, and actually improves in the up-to-air range, although it is still below the level when the pressure is in the low range.

It is important to realize that none of the techniques discussed here cover the full range of pressure inside a VI from the low pressure to up-to-air. Each covers a certain range, and this is highlighted in the text and in Table 3-3. The results of certain methods are also a function of the design of the VI. Additionally, the output of some methods can be affected by the composition and pressure of the surrounding gas that could potentially leak into the VI. The two main situations are air at atmospheric pressure, and 1.0-1.5 bar absolute pressure of SF_6 gas (generally used in GIS switchgear). The following discussion focuses on VI's in air. Table 3-3 summarizes the general application in SF_6 environments, and the discussion for each method goes into more detail, including practical issues of using the method with GIS switchgear. Table 3-3 also summarizes the output of the test methods.

Table 3-3: Comparison of vacuum level measurement methods, including the vacuum level that can be measured, whether the measurement is affected by the design of the VI, the type of output, and compatability with SF_6

Method	Vacuum level	Design dependent?	Output	OK for SF6?
Magnetron	low to mid	yes	pressure level	yes
dielectric testing	mid to up to air	no	pass/fail	not generally
vacuum gauges	low to mid	no	pressure level	yes
mechanical pressure	up to air	no	pass/fail	yes
partial discharge	mid	some	mixture	unknown
field emission	low	yes	pressure level	yes with calibration
current interruption	mid	yes	pass/fail	yes with calibration
sound waves	up to air	yes	pass/fail	yes with calibration
light emission	up to air	yes	pass/fail	yes with calibration

The extensive use of vacuum interrupters in medium voltage switchgear [Slade2007a, Taylor2014] is raising the issue of how to confirm the vacuum integrity in the field, particularly after multiple decades in service [Falkingham2012]. Inspection of VI's after more than 20 years of field use have shown mixed results [Falkingham2012, Holdsworth2015]. It must be noted, however, that the VI's are only one part of a system; the rest of the system including the mechanism, control circuitry, circuit design, etc., must also function in order for the VI's to fulfill their role.

3.3.13.1 Magnetron Method

APPLICATION

The magnetron method is well established during the production process and is applied as a routine test to guarantee the integrity of the vacuum. However, it potentially can be used in a mobile test system for on-site-measuring of the internal pressure in VIs [Cadick2014b, Eichhoff2013]. But the conditions to apply this method on an installed VI and the design of modern vacuum circuit breakers, i.e. employing casted pole parts with embedded VIs, can significantly reduce the accessibility of the VI to perform the measurements. In general, the magnetron method must be differentiated between the stationary application during manufacturing and the two alternatives for mobile application related to the way of generating the magnetic field. However, the stationary application is only listed as reference for the two mobile versions as it is out of the scope of this TB, because dismantling of vacuum switchgear in order to move the dismounted VIs to the stationary test facilities of the manufacturers must be considered intrusive. For Mobile application magnetic field can either be applied by coils [Cadick2014b] or permanent magnet arrangements [Eichhoff2013], see Figure 3-43.

Figure 3-43: Left: Permanent magnet arrangements as two exemplary devices for the generation of the magnetostatic field [Eichhoff2014a], Right: Flexible coil system for the generation of the magnetostatic field [Cadick2014b]

As vacuum interrupters dominate in the medium voltage range, this is the main field of application for the magnetron method. First installations of vacuum circuit breakers in the high voltage range have been carried out [CIGRE_589_2014], however no constraints can be identified to apply the magnetron method on VIs for higher voltage ratings accordingly.

All magnetron methods are based on single measurements that can be re-run after a specific service time. Continuously measuring variants that can serve as online monitoring systems would require a modification of the VI, i.e. by attaching vacuum gauges [Mao2007], and thus are excluded due to their intrusive nature.

MODE OF APPLICATION

Mobile magnetron (coils)	**Periodic Measurement**	✔	Continuous Monitoring
Mobile magnetron (permanent magnets)	**Periodic Measurement**	✔	Continuous Monitoring

The application of the magnetron method requires direct access to the VI itself or at least to the pole part, the VI is embedded in. Thus, the method can only be applied on AIS, where the circuit breakers can be easily removed after disconnection. Whereas in GIS the breaker poles generally are integrated in the SF_6 insulated compartments of the MV switchgear and, hence, are only accessible by intrusive measures.

THEORETICAL BACKGROUND

Basically, the magnetron method is an indirect pressure measuring principle using the VI as its own gauge. It is based on the correlation of the pressure p and a discharge current I according to $p = K \cdot I^{\alpha}$ with $\alpha \approx 1 \ldots 1.4$ and a constant factor K, depending on i.e. the applied testing parameters. The direct test voltage and the magnetic flux density must be well defined to guarantee the reliability of the magnetron-based pressure measurement. Furthermore, the design and the size of the VI must be considered [Eichhoff2013].

DEGREE OF MATURITY

Mobile magnetron (coils) 

Mobile magnetron (permanent magnets) 

EASE OF USE AND CONSTRAINTS

Uncertainties can arise during the mobile magnetron test, especially from the Getter-Ion Effect that emerges from gas adsorption on the metallic surfaces inside the VI. The analysis of the Getter-Ion Effect shows that the temporary gas binding considerably limits the repeatability of the magnetron measurement [Eichhoff2014a]. Furthermore, any switching operation (even the disconnection of the VI in preparation of the measurement) has an effect on the residual gas composition and the total pressure inside the VI. Hence any single measurement on-site only provides a singular recording of the present pressure value, which only contains information regarding the instantaneous condition of the internal pressure. However, any forecast on the pressure development unavoidably requires the consideration of the entire service life and previous measurements in order to gain reliable information. Thus the analysis of the internal pressure measurement must be done by an expert system taking these effects into account [Eichhoff2013]. Limitations regarding the applicability and measuring range can arise from the compact design of modern vacuum circuit breakers that possibly does not provide sufficient space to install the magnetic field device. Furthermore, additional design factors, i.e. the embedding of the VIs in casted pole parts have to be taken into account. [Eichhoff2014a].

3.3.13.2 Dielectric Vacuum Testing

APPLICATION

This method incorporates two main techniques both of which apply a high voltage across the open vacuum interrupter contacts [Slade2007]. Failure of this test consists of electrical breakdown inside of the vacuum interrupter. The first technique uses an AC voltage of ~80% of the rated power frequency withstand voltage. The second uses DC voltage. This DC method is generally used in the so-called "vacuum checkers" that are commercially available (see Figure 3-44). The voltage level for the DC method needs to be at approximately the peak voltage of 80% of the rated power frequency withstand voltage to ensure detection over the pressure range. Therefore, the DC method needs to use different voltages for VI's at different system voltage ratings. If too small of a voltage is used, then the VI may be able to hold off the voltage when filled with gas. If the voltage is too high, there is the risk of over-stressing the VI and having an external breakdown. Although a comparatively low voltage is sufficient to detect a VI near the Paschen minimum breakdown voltage, this would allow for only the detection of very specific failure modes and/or specific time periods and would fail to detect VI's that are up-to-air.

The dielectric methods can detect pressures in the mid to up-to-air range. In order to apply the voltage over the open contacts, the breaker or switch must be disconnected from the power system and connected to the appropriate power supply, making this a periodic test. The breakdown inside the VI is controlled by the breakdown of the gas between the contacts [Slade2007], and therefore is mostly independent of the VI design. However, it does depend on the contact gap, which is in turn a function of the system voltage. Both methods can be applied to the full voltage range of VI's, from low to high voltages, however the voltages for high voltage VI's can be high enough to require special attention to the generation of x-rays during the test [Slade2007]. The vacuum interrupter manufacturers can provide detailed guidance [CIGRE_589_2014].

MODE OF APPLICATION

Periodic Measurement ✔	Continuous Monitoring

THEORETICAL BACKGROUND

Dielectric vacuum testing methods observe an electrical breakdown in the gas between the VI contacts. The Paschen curve behavior dictates the breakdown voltage [Slade2007]. For VI's in air, pressures from 10^{-3} hPa to up-to-air lead to a breakdown voltage below ~80% of the rated power frequency withstand voltage. For VI's in SF_6, the situation can be more complicated. If there is a leak large enough to back-fill the VI with some pressure of SF_6 as is in the chamber, the dielectric performance of the SF_6 especially when combined with a fill pressure above 1 atm (abs) can lead to the VI withstanding the applied voltage.

The output of the method is a pass/fail measurement of the vacuum level. Passing generally means the pressure inside the VI is below 10^{-3} hPa, and failing that the pressure is above this level. These methods offer no guidance to what level the vacuum is at when the test passes, other than it is lower than 10^{-3} hPa.

Both the power frequency withstand and DC voltage measurements are well developed techniques, and are already extensively applied in field with commercial products available.

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

Both techniques require the breaker or switch to be disconnected from the grid. Generally these tests are performed during maintenance. The equipment for the DC voltage test is often very compact and is generally man-portable. Equipment for the power frequency withstand tests is more substantial, and can be challenging to bring to every field site. The techniques require careful application for VI's in SF_6, since SF_6 can provide sufficient insulation to prevent breakdown when the VI is backfilled with SF_6.

The power frequency withstand and DC voltage tests are generally recommended [Slade2007a, Holdsworth2015], with certain caveats for the DC tests. The main risks with dielectric vacuum testing are associated with the DC method. Particularly for high system voltages, the DC test can misinterpret field emission current from the contacts as a high vacuum level [Slade2007a]. This risk can be mitigated by testing both polarities, since the field emission is generated from the cathode, and there is a reduced likelihood to have a high field emission from both contacts. The risk can be further reduced by using the DC test as a screening test, identifying VI's for further testing with the power frequency withstand test.

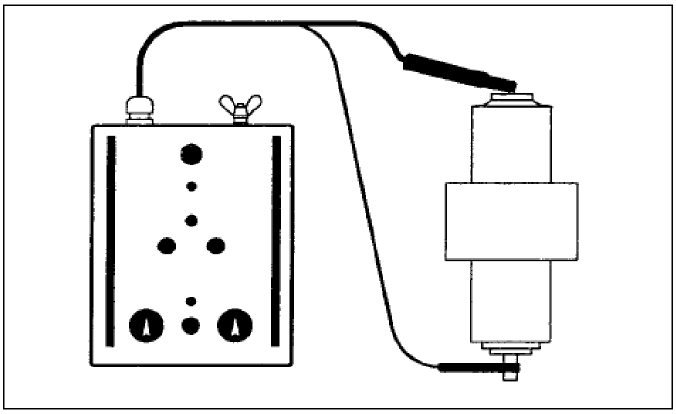


Figure 3-44: Typical setup for a DC measurement of vacuum integrity [Megger2012]

3.3.13.3 Vacuum gauges

APPLICATION

The method involves incorporating a vacuum gauge directly into the vacuum interrupter, so that the pressure can be directly measured. The two main techniques would be building the VI with a cold cathode [Mao2007] or a spinning rotor gauge [Schellekens2014]. The gauge would need to be brazed or in some other way permanently attached to the VI. The means that the materials used in the construction of the gauge would need to be able to go through the brazing cycle of the VI with temperatures between 800-900° C.

Both techniques are regularly used in the monitoring of actively pumped vacuum systems. These provide measurements from the low to mid vacuum range, and could (at least conceptually) provide continuous monitoring of the vacuum pressure. Since the pressure is measured locally at the gauge, the gauges do not need to be calibrated or adjusted to the particular VI design, as long as there is sufficient space to mount the gauge on the VI. Naturally the calibration for the particular gauge type would need to be known beforehand. This technique would be applicable for low, medium and high voltage VI's.

MODE OF APPLICATION	Periodic Measurement	**Continuous Monitoring** ✔

THEORETICAL BACKGROUND

The cold cathode gauge operates under the same principle as discussed in the magnetron section. The magnetron method essentially uses the entire VI as the cold cathode gauge. The cold cathode gauge requires a magnetic field to increase the chance of a collision with a molecule and a potential difference (usually in the kilovolts range) between the two electrodes. The current drawn between the electrodes is then proportional to the pressure (Figure 3-45).

The spinning rotor gauge uses a small metal ball that is magnetically levitated and driven to rotate (Figure 3-46). The rotation rate is affected by the presence of gas, which increase the viscosity and reduces the rotation rate. This rate is measured and is then proportional to the pressure.

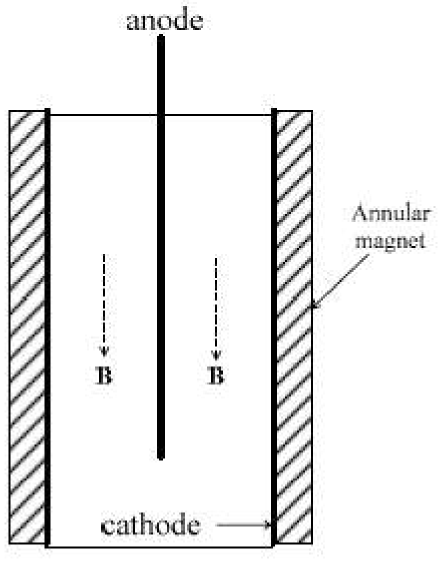


Figure 3-45: Basic design of a cold cathode gauge [Mao2007]

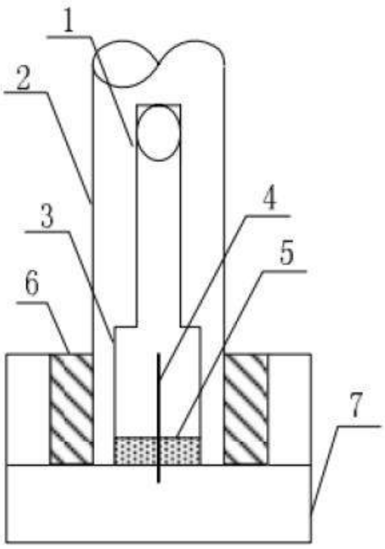


Figure 3-46: Spinning rotor gauge including the rotating metal ball (1), metal housing (2), combined with a magnetron gauge including the cathode (3), anode (4) and permanent magnetic (6) [Mao2007].

Both devices provide an actual measurement of the pressure. Both designs have been built onto sample VI's for research purposes. To date, there has not been any known application of these techniques outside the research environment.

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

Both types of gauges need to be built-in to the VI from the start. There is currently no practical way to introduce the gauges to VI's after production. The gauges could be used when the VI is in SF_6 with the appropriate calibration.

The main difficulty in the application of these gauges (after the initial attachment) is making the electrical connections to the gauges. For the cold cathode gauge, the voltage to the electrode must be separate from the ground, and also not interfere with the high voltage performance of the VI. In addition, the current between the gauge electrodes is very small, and this signal must be accurately transmitted without significant interference from the surrounding high currents and high voltages. The spinning rotor gauge requires connections for driving the gauge and detecting the resulting motion. Again, these signals must function in the high current and high voltage environment.

The reliability of the vacuum gauges in the electrically noisy and high voltage environment of the power grid means that the failure rate of the diagnostic itself would be expected to be much higher than the failure rate of the VI's. Research on the attachment of these gauges to the VI's has focused on the fundamental feasibility of the method and not on the reliability of the measurement system in the field. Magnetic fusion and accelerator experiments have developed various informal methods to allow the monitoring of the vacuum pressure in high voltage and electrically noisy environments. Methods include extensive metal shielding of the sensor, electronics, and cables; switching the sensor off or blocking the signal during noise-generating events; and positioning of the sensor and electronics to maximize distance from noise sources. However it is unclear if these techniques are applicable or reliable enough to be used in a power grid environment, nor have these techniques been systematically grouped and evaluated.

3.3.13.4 Mechanical pressure monitoring

APPLICATION

Atmospheric pressure produces a significant closing force on the moving terminal of the VI's. For VI's used in circuit breakers, this force is typically on the order of a few hundred newtons. When the vacuum is completely lost, the external atmospheric pressure is balanced by the same pressure inside the VI, and the closing force is significantly reduced, leading to a change in the mechanical behavior of the VI. Diagnostic methods looking for this change can only detect when the VI is completely up-to-air. For example, even the very "high" pressure at the Paschen minimum is more than sufficient to maintain the full closing force on the VI.

The main method for mechanical pressure monitoring attaches an additional moving part to the VI using a bellows or similar (Figure 3-47), and the complete loss of vacuum then results in the motion of this component [US7302854]. This additional part is free to move, unlike the moving contact which is constrained in its motion by the circuit breaker mechanism. A detection system then observes the different position of the additional moving part, and reacts accordingly. Depending on the detection system, this setup can continuously monitor the VI. The motion of the additional moving part is dictated by the design of the additional part and not of the overall VI, therefore it is independent of the particular VI design. The method could be applied to low, medium and high voltage VI's.

It is theoretically possible to use the closing force on the moving terminal of the VI to observe the loss of vacuum. Atmospheric pressure normally applies a force on the order of a few hundreds of Newtons to the VI moving terminal. For comparison, the circuit breaker applies a closing force of typically a few thousands of Netwons. Therefore, the loss of closing force on the VI can be difficult to determine from the mechanical behavior of the breaker, because of the small size of the VI closing force as compared to the circuit breaker closing force. For vacuum contactors, the lower force from the contactor mechanism might allow a diagnosis of complete vacuum loss from the mechanical behavior.

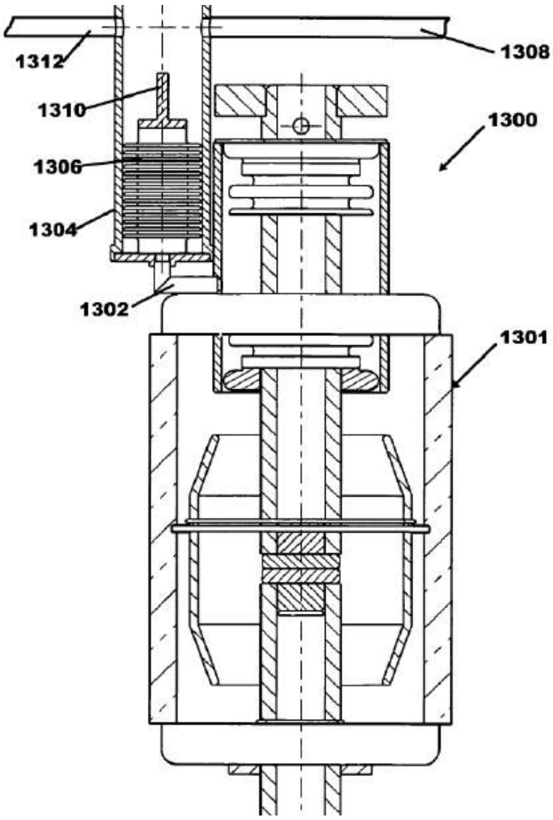


Figure 3-47: Pressure monitoring via an additional bellows (1306) attached to the VI (1301). A tube connects the additional bellows to the VI (1302), and the movement of part (1310) during loss of vacuum breaks the light path between (1308) and (1312) [US7302854].

MODE OF APPLICATION

Periodic Measurement	**Continuous Monitoring** ✔

THEORETICAL BACKGROUND

The technique measures a mechanical change due to the loss of the closing force from the atmospheric pressure on the moving terminal of the VI. This technique would only provide a pass/fail measurement of whether the VI was up-to-air or not. The pressures around the Paschen minimum and other points where the VI performance starts to be affected are far too low to produce any detectable mechanical change.

A key part of the measurement method is the detection system. One implementation uses an optical system to detect the motion [US7802480]. The motion disturbs an optical path between two fibers, either stopping the light transmission, or allowing the light through by inserting a mirror or removing a block. The light can be guided through fiber optics to the detection system. This maintains an electrical separation between the VI and the measurement system, and allows the electronics to be placed in the low voltage compartment of the switchgear. A second implementation uses the motion of the additional part to make or break an electrical connection. Since this contact must be electrically isolated from earth, this signal must be converted into an optical signal for transmission along a fiber optic, or be converted into a wireless signal (RF, etc.). This requires a microelectronic circuit near the VI to convert the signal, together with some method of powering the circuit while maintaining the electrical isolation.

Mechanical pressure monitoring has been implemented into prototype products from one manufacturer. The field experience with this method is not known.

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

The moving part needed for the pressure monitoring must be installed on the VI during its initial manufacturing. There is no possibility to add this to already built VI's. It is conceivable to add VI's with this feature to existing circuit breakers, along with the monitoring equipment. However, the practical issues with fitting a VI with the extension for the extra part into existing equipment will most likely prevent this. The method is generally compatible with SF_6, oil, and solid insulation as long as practical issues of space, guiding the light to the detection equipment, etc., can be dealt with.

The main risk is the reliability of the measurement equipment as compared to the VI's. In general, the additional parts brazed to the VI lead to additional potential leak paths. Also, these components can be more fragile and/or vulnerable to damage during installation that can lead to a loss of vacuum. The optical technique has the advantage of moving the non-optical components into the low voltage compartment of the switchgear. However, fiber optics are vulnerable to misalignment of the two fibers, damage on installation, blockage by condensation or dust, etc. The electrical contact method of motion detection needs a powered microcircuit near the VI that is also electrically isolated. This creates several potential failure modes related to the microcircuit reliability, successful transmission of the signal, powering of the circuit, and maintaining the electrical isolation.

3.3.13.5 Partial discharge (PD)

APPLICATION

Partial discharge is a well developed technique often used to detect defects and voids in solid insulation. The application of an AC voltage below the breakdown voltage can generate microdischarges. These microdischarges transfer some pico-coulombs of charge, and can be detected with specialized equipment. In vacuum, various features of the partial discharge signal change with the internal pressure of the VI [Yokomichi2016]. These systems could detect vacuum levels in the mid-range (Figure 3-48). The performance in the up-to-air region is unknown. Acquiring a PD signal requires a voltage difference in the VI; generally this would be over the open contacts. The need to open the contacts and stop the power flow leads to a periodic measurement of the pressure. The PD signal could be dependent on the design of the VI; this point needs to be further investigated. In general, the technique is applicable to medium and high voltage VI's.

One implementation describes a method using the potential difference between the closed contacts and the floating center shield. As the voltage oscillates on the closed contacts, the voltage difference to the shield could give a PD signal. This signal can then be monitored to give a continuous monitoring of the VI pressure [Schellekens2015]. It should be noted that the main voltage difference is between the closed contacts and ground. Unless there is a ground plane very near to the VI, the voltage on the floating shield will be very close to the voltage on the contacts. This reduces the voltage considerably below the phase to ground voltage, and could be a significant limit on the magnitude of the PD signal.

In general, the output of both systems would depend on the VI design and voltage level, since the electric field that generates the PD is a function of the general VI layout, where the voltage is applied, and the magnitude of the voltage.

MODE OF APPLICATION

Periodic Measurement	**Continuous Monitoring** ✓

THEORETICAL BACKGROUND

At the low pressure range, voltage between the contacts in vacuum can produce field emission current which is independent of the pressure in this range. Microdischarges can produce charge transfer similar to partial discharge, however the microdischarges are driven by the local surface conditions (roughness, particles, etc.) and not by the pressure between the cathode and anode [Slade2007]. As the pressure increases into the mid-range, PD activity starts. The largest change in the activity magnitude occurs when moving from the low to the mid-range pressure zone. There is evidence that the resulting PD activity level is pressure dependent, however the magnitude of the variation with pressure may be difficult to practically measure in non-laboratory conditions. Therefore, such a system could provide a pass/fail indication, possibly with some measurement of the pressure level.

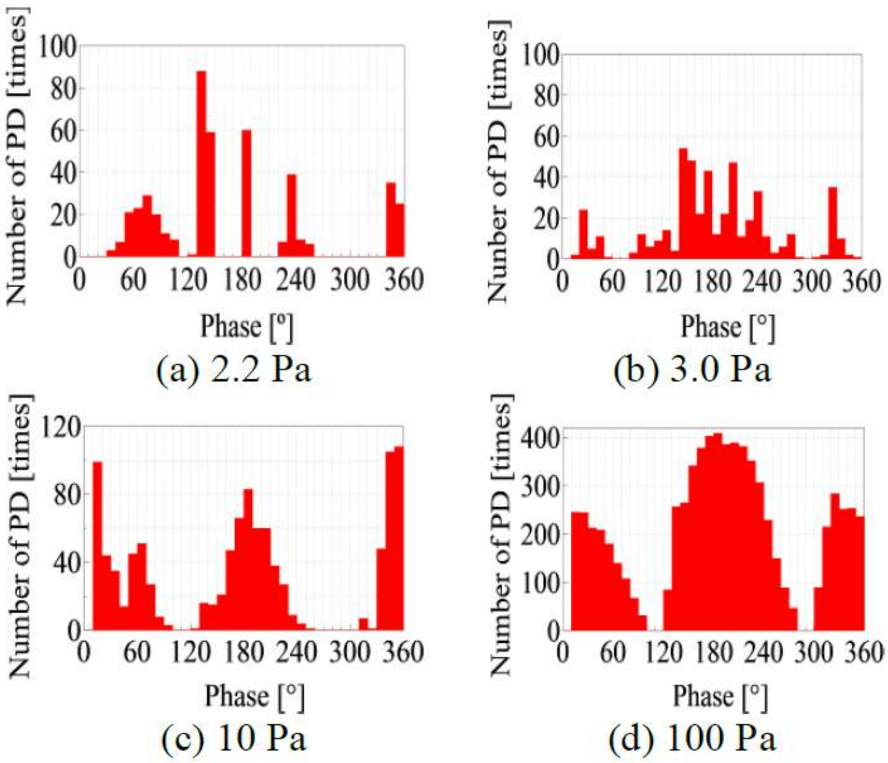


Figure 3-48: Number of partial discharges as a function of the phase angle of the voltage and pressure level inside the VI [Yokomichi2016a]

One manufacturer has designed a prototype measurement system for a vacuum circuit-breaker, and performed initial tests on this device [Schellekens2015]. Other work is confined to the laboratory.

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

The device described in [Schellekens2015] could be retro-fitted to existing vacuum circuit breakers (Figure 3-49) when the center shield is accessible (i.e. not in an encapsulated pole, not in other external insulation, etc.), has sufficient space and is reasonably calibrated to the VI design and voltage level. In general the system should work in either air or SF_6; however the system might need to be calibrated for the surrounding gases.

The main risks of the use of PD to detect the vacuum level are, again, the reliability of the diagnostic as compared to the underlying system. Specifically for PD detection, the magnitude of the signal from the PD is very small, and the signals can require analysis of the phase dependent behavior to determine the pressure. This can make the system vulnerable to drift of the measurement system over time, temperature effects, etc. These points would need to be investigated.

Figure 3-49: System for monitoring the PD from in-service circuit breakers. System could be installed as a retro-fit, or built-in with the breaker [Schellekens2015].

3.3.13.6 Other experimental techniques

APPLICATION

This section contains vacuum pressure measurement techniques that have been proposed and/or initially tested in the published literature, but would be difficult to implement in the field or currently have very limited evidence to support the application of the methods in the field.

The first group consists of techniques measuring changes in electrical behavior between the contacts. These include field emission from open contacts [Frontzek1993], and the current interruption behavior [Merck1999]. The field emission measures pressure changes in the low range, and the other technique measures the pressure in the mid-range. The measurements require specialized equipment, and therefore could only be performed periodically, mainly during maintenance periods. The output would generally be a function of the VI design; however the techniques should generally be applicable to high-voltage VI’s.

The second group consists of techniques measuring signals passing through or emitted by the VI. One option uses sound waves projected through the VI, and then observes a difference between the VI under vacuum and filled with gas [US7383733]. Since sound wave propagation requires a non-trivial pressure, it is likely that this technique is only useful in the up-to-air range of pressures. The second option uses light emitted during arcing by observing the arc through a transparent portion of the ceramic and holes in the arcing shield [US7802480]. The amount of light emitted for a given current can increase with pressure, given a potential measurement of the pressure. In general arcs at or around atmospheric pressure are much brighter than arcs at lower pressure, therefore this technique could be used in the up-to-air range. The sound based technique could be continuously employed, if the equipment can be electrically isolated from the VI. The light based technique requires opening the contacts while passing current. This can only be done periodically. Both techniques are affected by the VI design, and both in general could be applied to high-voltage VI's.

MODE OF APPLICATION

Field emission	**Periodic Measurement ✓**	Continuous Monitoring
Current interruption	**Periodic Measurement ✓**	Continuous Monitoring
Sound waves	Periodic Measurement	**Continuous Monitoring ✓**
Light emission	**Periodic Measurement ✓**	Continuous Monitoring

THEORETICAL BACKGROUND

Variations in pressure can alter the breakdown voltage between the contacts, as discussed in the dielectric vacuum testing section. Field emission consists of low (generally micro-amps) current driven by the emission of electrons from localized points on the cathode contact surface when a high voltage is applied. The presence of gases modifies the work function required to extract electrons from the solid. The technique outlined in [Frontzek1993] uses a high-frequency arc to clean the contact surfaces, removing the absorbed gas. This increases the field emission current. As the field emission decays to its previous value, the decay time can be correlated with the pressure. The maturity of this technique is limited to R&D activity.

The current interruption technique uses one of two general types of circuits [Merck1999]. At a certain pressure that depends on the circuit being used, re-strikes (failures to interrupt) start to occur. The circuits in the paper were tested on one VI at one voltage level, so it is unclear how to generalize the results for different VI designs and for different voltage levels. Another technique mentioned in the same paper monitors the number and height of arc voltage spikes during the burning of a 9.7A arc between the contacts. The number of voltage spikes reduced significantly above a certain pressure. The maturity of these techniques is also limited to R&D activity.

The basis of the sound technique is that low pressure limits the transmission of sound waves through the VI. When the VI is up-to-air, the gas inside allows the sound waves to propagate, without this gas the sound waves are limited to traveling through the solid parts of the VI. When an ultrasound system is coupled to the VI, this difference could be detected (Figure 3-50). The output of the system would be a pass/fail measurement, and the technique is limited to R&D activity.

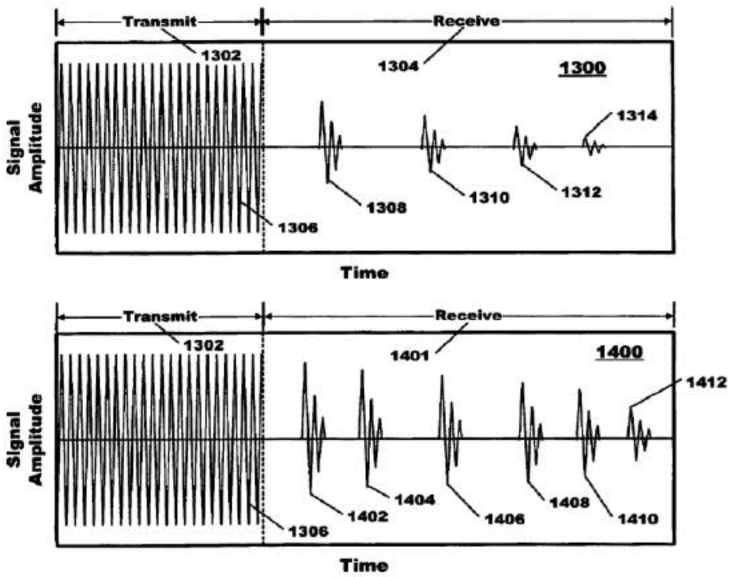


Figure 3-50: Difference in the received signal for the sound detection technique for a VI under vacuum (top) and up-to-air (below) [US7383733]

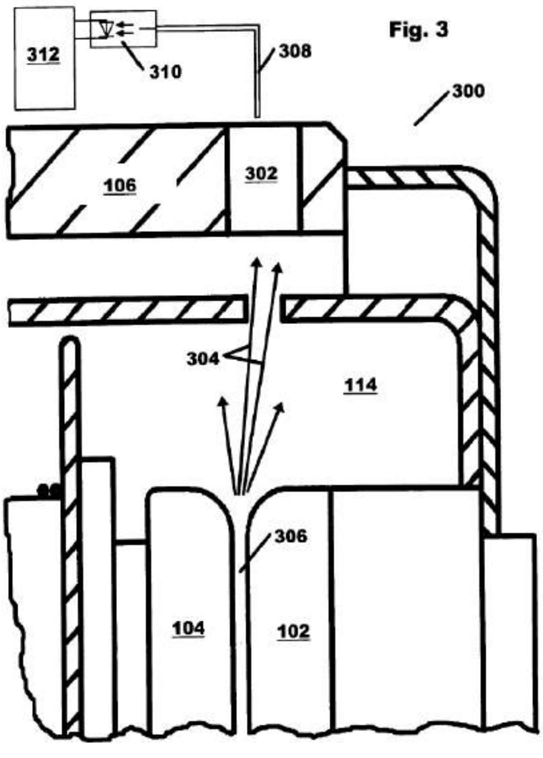


Figure 3-51: System for detecting the level of light emission during arcing in VI's [US7802480]. Arcing between the contacts (102) and (104) generates light emissions (304), which pass through a transparent portion of the insulating housing (302). The light is gathered by a fiber optic (308) and trasmitted to a detector (310).

The final technique measures light emission during arcing. Light is generally emitted during arcing; the technique uses the significant increase in light emissions when the arcing occurs in a gas. This requires a transparent portion of the insulating housing of the VI, and holes or a viewport through the shield that surrounds the arcing contacts (Figure 3-51). The light emissions are proportional to the current level and also depend on the arc control technique in vacuum. Therefore, the measurement system needs to distinguish whether the increase in light is from a higher pressure or a higher current level, and be calibrated to the VI design. A significant increase in the light emissions would be restricted to the shift to the up-to-air range, making this a pass/fail test. This technique is also currently limited to R&D activity.

DEGREE OF MATURITY

Field emission

Current interruption

Sound waves

Light emission

EASE OF USE AND CONSTRAINTS

The field emission and current interruption techniques both can only be performed during maintenance periods and require a significant amount of equipment to generate the voltage/current and make the detailed measurements needed for analysis. The sound method could conceivably be retro-fitted to existing systems, provided the waveguides to concentrate the sound signal through the VI could be electrically isolated from the high voltage and not interfere with the operation of the breaker. Once installed, the sound method could provide continuous monitoring since it is independent of the operational state of the breaker. The light emission method requires that the specific features required to observe the light be built into the VI from the start. If the light detection system can be electrically isolated from the breaker, then the method could be used on breakers in service. However, a signal will only appear when the VI opens on a current. This means that either the test is only performed when the breaker opens in operation (and the detection system is continuously available for this event), or the breaker must be deliberately opened when current is flowing. The current could be from the power system, or supplied by a separate source if the test is performed with the breaker out of regular service.

All four techniques would generally be applicable for VI's in SF_6, however, since these methods depend on the behavior of the gas inside the VI, they would need to be calibrated (or the operation confirmed) with the SF_6 gas.

The primary risks with the field emission and current interruption techniques are the difficultly with interpreting the results. Field emission current and multiple re-ignitions are active subjects of current research, and the interpretation of these signals even in a research environment is challenging. The statistical scatter of the data is significant, and this is combined with a limited understanding of the effect of the local contact conditions (based on previous breaker operations, contact material, etc.) on the signals. The reliability of measurements of voltage fluctuations requires significant further research to understand its reliability.

The sound method had the general risk of the reliability of the diagnostic as compared to the underlying VI failure rate. The complex dependence of light emission strength on the pressure level, current level, arcing time, VI design and contact material make isolating the pressure level difficult in the field without extensive expertise. The requirement that the breaker open with current significantly reduces the value of the technique for continuous monitoring, since the main goal of continuous monitoring is to prevent operations on compromised VI's.

3.3.14 Vibration

A vibration signal will arise during the opening and closing process of the circuit breaker. It contains a lot of information which can indicate a healthy status of the equipment, such as the moment of arc contact opening. Since vibration signals can be measured in non-intrusive ways which enhance its anti-interference ability significantly, vibration signal measurement in electrical equipment field monitoring has drawn much attention of researchers.

3.3.14.1 Measurement of arc contact ablation

APPLICATION

The circuit breaker arcing contact gets progressively shorter while it is ablated during each operation. During the opening operation of the circuit breaker, the main contacts open first; then with minimal time elapse the arcing contact opens. Therefore, measuring the time between opening of the main and arcing contacts would indicate the degree of ablation of the arcing contacts.

A non-invasive direct ablation measurement method based on vibration signal analysis has been developed [Ukil2013] for application on high-voltage circuit breakers. In this system, the delay in the time instant of the start of the arcing contact touch as it gets shorter due to ablation is monitored. The relative experiment environment is exhibited in Figure 3-52. The proposed method consists of measurement of the vibration signal from the shell of the circuit breaker by use of an accelerometer. The acquired data can be used in two ways. One consists of comparing the acquired vibration pattern with a reference record and quantifying the difference. The other is used to detect the time interval.

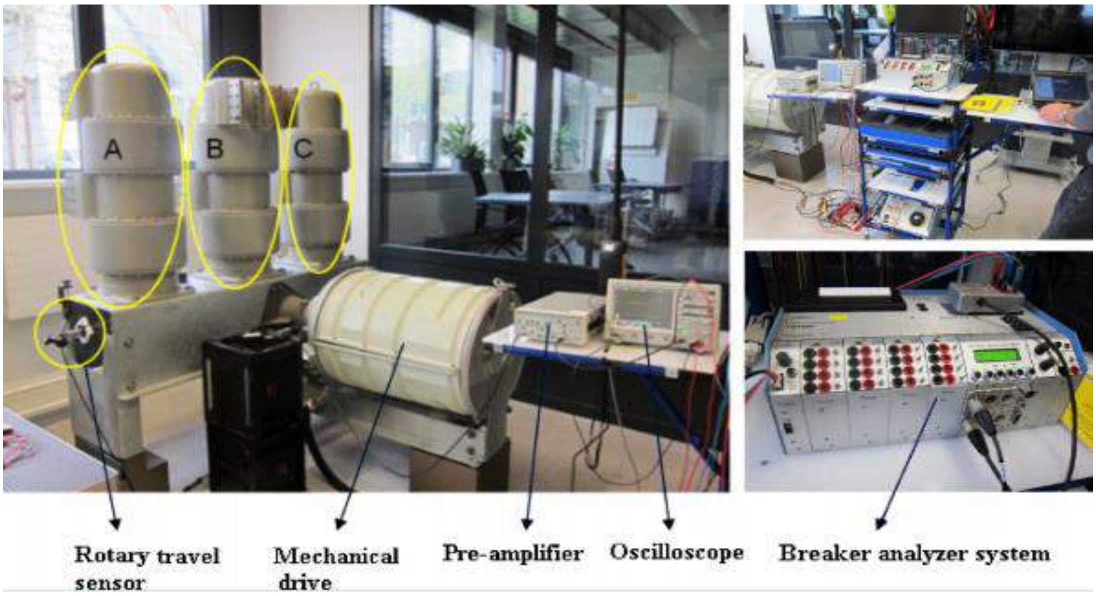


Figure 3-52: Measurement setup for three pole circuit breaker [Ukil2013]

MODE OF APPLICATION

Periodic Measurement	✓	Continuous Monitoring

When the sensors are attached near the arcing contact system, the three poles with different levels of ablation manifest distinct vibration signals.

THEORETICAL BACKGROUND

For an old breaker, as the arcing contact gets shorter, there will be time delay for the arcing contact instant, hence the time difference would be shorter. In practice, the nominal contact would not be ablated much; therefore, as shown in Figure 3-53, the nominal contact instant t_{Nom} would practically remain constant, while the arcing contact instant t_{Arc} would be delayed, during a closing operation.

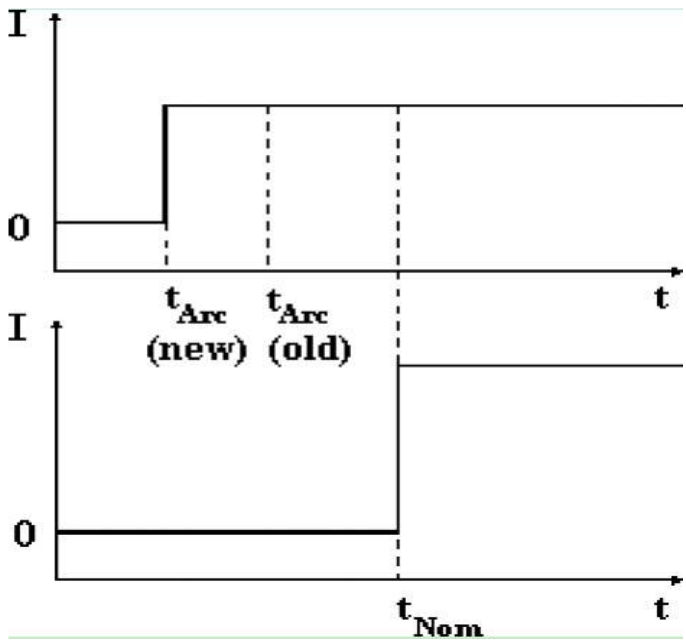


Figure 3-53: Timing difference of arcing and nominal contacts [Ukil2013]

DEGREE OF MATURITY 

EASE OF USE AND CONSTRAINTS

The method will not produce a valuable result unless all accelerometers are attached uniformly. What is more important, accelerometers must be placed in the arc extinguishing chamber to eliminate the vibration signal produced by drive-mechanism. However, some breakers are not suited for attaching accelerometers, such as porcelain pole breakers. Consequently, the method is not adapted to this kind of breaker.

What can be an advantage for adapting this method is that many utilities use tank type circuit breakers. The following tips are strongly recommended when applying this method in your project

1. All accelerometers must be attached uniformly. An important issue is the mounting of the sensors. Power tape should be used for mounting the sensor. In practice, one has to use super glue or similar methods, ensuring as uniform mounting as possible.
2. Embedded data acquisition system must be able to resist noise produced by the drive mechanism.
3. Some signal processing methods are required for distinguishing the instant of each event.

3.3.14.2 Detecting Mechanical Anomalies

APPLICATION

A dynamic time wrapping (DTW) algorithm [Landry2008a] for analyzing the vibration pattern aimed at detecting mechanical anomalies of the circuit breaker has also been developed. Three case studies were used to validate the algorithm, which confirm that the vibration pattern can be used as a diagnostic tool for all CBs (both medium- and high-voltage) whenever a mechanical anomaly is suspected.

In time series analysis, dynamic time warping (DTW) is one of the algorithms for measuring similarity between two temporal sequences which may vary in speed. For instance, similarities in walking could be detected using DTW, even if one person was walking faster than the other, or if there were accelerations and decelerations during the course of an observation.

The developers present typical graphs produced by the analysis software, such as the following Figure 3-54. The top left-hand-side graph depicts the reference signal comprised of three consecutive closing operations (F5, F6, and F7) of the phase-B operating mechanism which exhibits a normal vibration pattern. The bottom left-hand-side graph contains the phase C vibration signal (F6 and F7) to be analyzed and compared to the reference one (Phase B). As a result of the vibration analysis, the graph on the right-hand side contains three graphs: amplitude deviation with a peak value of 28.4 dB which triggers an alarm (i.e., 15 dB).

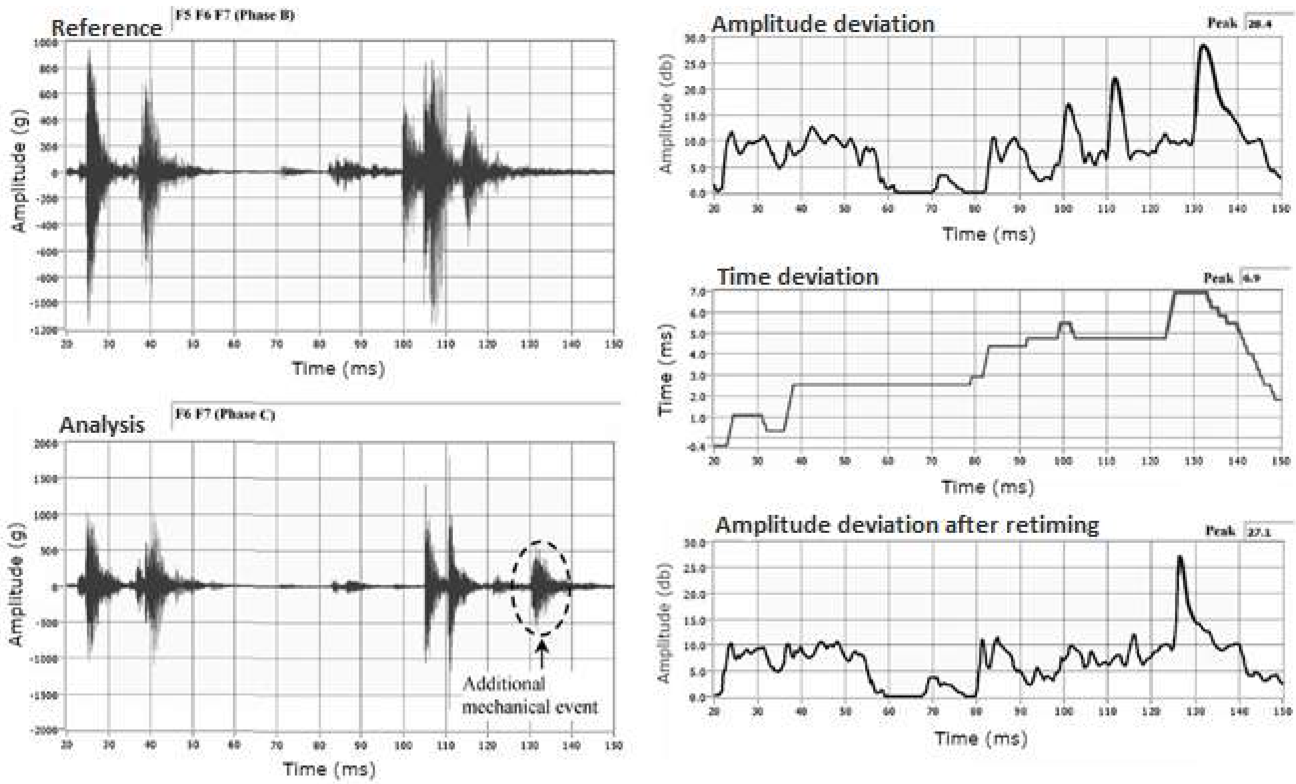


Figure 3-54: Graphs of the vibration analysis on a 230 kV CB [Landry2008]

MODE OF APPLICATION

Periodic Measurement	✓	Continuous Monitoring

THEORETICAL BACKGROUND

The diagnostic algorithm is based on calculating the distance (eg quantifying the difference) between two different vibration signal records, in the time-frequency domain, in order to compare a current signal to a reference.

Defining the following vibration signals in the time-frequency domain,

$$A = \{a_1, a_2, ..., a_n, ..., a_N\}$$

Equation 3-1

$$B = \{b_1, b_2, ..., b_m, ..., b_M\}$$

Equation 3-2

The distance can be calculated as follows:

$$D(A,B) = \frac{1}{N}\sum_{n=1}^{N} d(a_n, b_{m=w(n)})$$

Equation 3-3

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

The case studies presented here confirm that vibration analysis can be used as a diagnostic tool for all CBs whenever mechanical anomalies are suspected. It is anticipated that mechanical anomalies can be detected, which may arise from a large variety of causes such as defects in transmission shafts, loosening of internal parts in breaker interrupting chambers, low oil levels in closing and opening oil dampers, driving rod thread stripping, etc.

3.3.15 Visual Inspection

3.3.15.1 Visual inspection and Recording

APPLICATION

Visual inspection is a fundamental inspection method applied to all types of equipment in its in service state, useful in periodical prevention and discovering symptoms of deteriorated conditions [Kopejtkova2014]. Especially for switchgear, it is defined in IEC 62271-1 as "visual investigation of the principal features of switchgear and controlgear in service without dismantling".

Visual inspection is applicable to a large portion of components of switchgear including controls, indication, alarms, gas, air and hydraulic systemes as well as a variety of auxillary components.

The visual inspection is the most common of routine scheduled inspections, often providing the first indication of trouble.

Components visualy inspected may include:

- Trip/closing coils
- Auxiliary switches
- Wiring, joints and lugs
- Control, indication, alarm and various auxiliary relay
- SF_6 Gas density monitoring system
- Air, hydraulic or spring operating systems as applicable
- Anti-condensation device including thermostats heater and fans
- Control and mechanism doors, gaskets, insulation, vents and filters
- Switching control devices such as circuit breakers, fuses and switches
- A general external visual inspection of the physical condition including cabinets, switchgear, bushings and ground connections

Recorded information may include:

- Operations counters
- Operation timers
- SF_6 gas density
- Air or Hydraulic pressure
- Fluid levels
- Local alarms and indication

As a result of the visual inspection, more detailed investigation or testing, either in-service or off-service, such as infrared thermography or gas leak detection may be scheduled.

MODE OF APPLICATION

Periodic Measurement ✔	Continuous Monitoring

THEORETICAL BACKGROUND

This method consist of a visual inspection looking for possible anomalies: visible damage, burning/color changes, corrosion, loose parts, broken parts (ex.: exposed conductor), deterioration, dust, discoloration or sign of a problem like moisture, gas/air/hydraulic leakage arcing or overheating.

The method isn't strictly limited to purely visual items: it includes listening and smelling for abnormal conditions.

An important aspect of the visual inspection is the recording and evaluation on site of specifications such as SF_6 gas density, air or hydraulic levels and operations since the last inspection.

Additionally any local alarms are recorded and evaluated along with any abnormalities identified.

DEGREE OF MATURITY

Figure 3-55: Single pressure dead tank circuit breaker visual inspection – external (courtesy of FirstEnergy)

External visual inspection consisting of evaluation of the circuit breaker cabinet, interrupter housing, CT housing, bushing, SF_6 gas lines, couduit and grounding system.

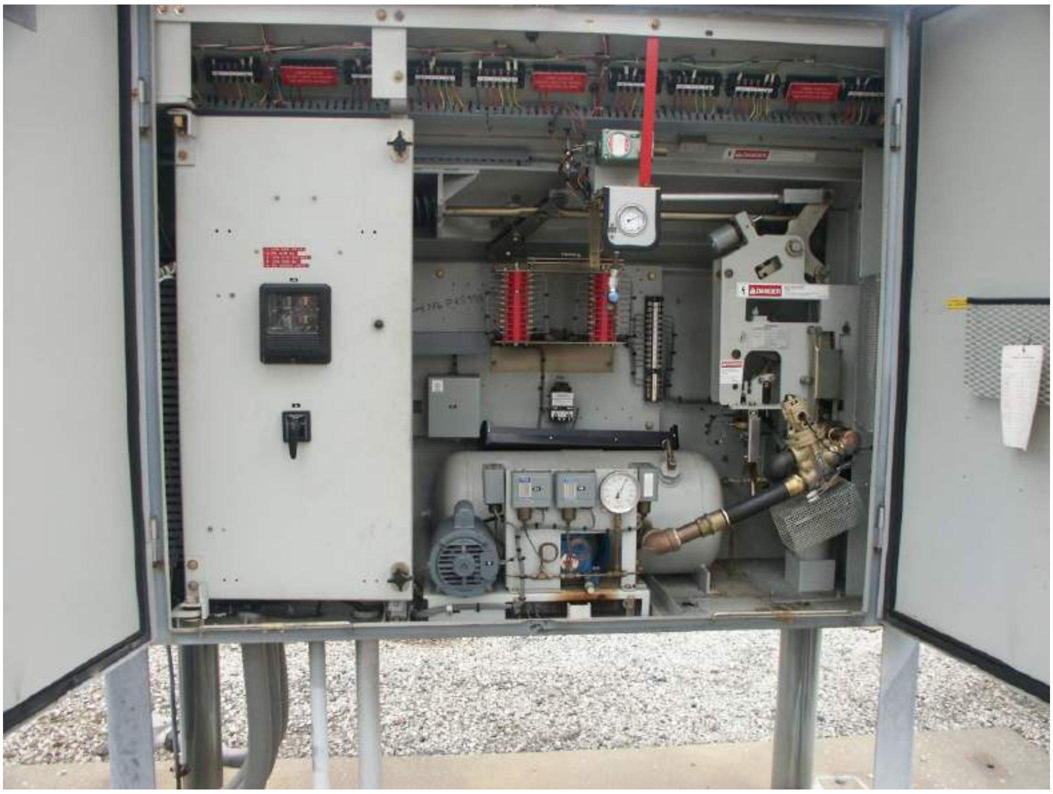


Figure 3-56: Single pressure dead tank circuit breaker visual inspection - controls, mechanism and alarms

Internal visual inspection consisting of evaluation of the air system, gas system, mechanism, auxiliary relays, wiring, connections and heaters.

Gas pressure, air pressure, operation counter and alarm indications are recorded.

EASE OF USE AND CONSTRAINTS

The switchgear visual inspection is a standard field practice as defined in IEC 62271-1 clause 7.2.1. It is often specified in manufacturer instruction books and documentation and is utilized for both MV and HV switchgear.

Visual inspection is fundamentally non-intrusive and performed in-service. It is performend on all types of Transmisiton and Distribution switchgear and controls.

Switchgear maintenance manuals provided by manufacturers (and eventually other relevant manufacturer documentation or utility maintenance procedure and failure analysis) are a good source for complementing the list of specific items to visually inspect.

3.3.15.2 Control and auxiliary circuits

APPLICATION

Controls and auxiliary circuits are not subject to complex diagnostic methods i.e. involving technological solutions and analysis of symptoms or condition indicators. Instead their status and proper operation are verified directly.

Mode of application: continuously monitoring, data can be available during each CB operation; except for functional tests that are mainly done periodically when the breaker is not on duty.

MODE OF APPLICATION

Periodic Measurement	✓	Continuous Monitoring

THEORETICAL BACKGROUND

Many signals, such as coil currents, auxiliary contact operation, supply voltages and environmental parameters of the cabinets, may be evaluated and are often continuously monitored by automation or monitoring systems. The following status parameters can be obtained: trip or close timing (slow/fast), circuit continuity, sequence of operation, auxiliary switch condition, maladjustment of coils, battery and charger status [CIGRE_167_2000] [Djekic2007].

Tripping or closing coil current depends on the source (battery) voltage and coil impedance which is a function of coil resistance and mechanical restriction on plunger. Therefore, analysis of the coil current profile during switchgear operation can provide valuable information about the operation mechanism (section "Coil current profile") but also about battery status and the coil itself [CIGRE_167_2000]. For evaluating the latter, the value of coil current at the end of the operation, when the current is stable, is used. Multiple shallow bumps (slight saw tooth), multiple deep and abrupt humps may indicate a loose wire in the trip circuit [Rogers2007].

On some kinds of switchgear, a motor is used instead of a coil. In this case, the motor current profile is used.

Battery and charger status is usually verified by voltage measurement. The problems with charging systems can be found by voltage level. The degradation of a battery may be found by measuring the voltage drop when the CB operates. Most of the time, the simplest way is to measure voltage at the trip coil and/or closing coil [Levi2010] but measuring voltage at each cell gives better results [Picagli2013].

Trending is the most useful data analysis method applied for control and auxiliary circuits. Trending consists of verifying if the signal is in the normal range, has consistent behavior with other information and is not drifting or abnormally fluctuating. Examples of measurements to follow by trending are:

- Operating environmental conditions (temperature and humidity)
- CB mechanical operation counter: can be validated by monitoring the number of operations by automation data. The mechanical counter can double count, stay with a frozen count, had been manually reset by mistake or replaced (subject related to section "History of operation")
- Count of recharging system: monitoring of number of operations of the recharging system allows verifying consistency with the physical counter, but also is a way to detect problems in the recharging system by discerning an anomaly in the maximum run time or the number of starts/day (see 3.3.16.2)
- Status of auxiliary switches (verification of timing and correct behavior)
- Other auxiliary services: power sources (DC, AC, mechanical, electromagnetic, thermal, etc.) and other supplies like high pressure supply (hydraulic, pneumatic, etc.). For example, the monitoring of air pressure allows discerning starts and stops of the compressor and consequently gives the total time of operation of the compressor. This could be used to validate the mechanical counter on the compressor.

Other parameters may be included according to manufacturer documentation, trending of secondary parameters may sometimes be useful in finding the symptoms of a more important problem.

DEGREE OF MATURITY

Diagnostics of controls and auxiliary circuits

EASE OF USE AND CONSTRAINTS

Most of these measurements are in-service and non-intrusive except for functional tests that are mainly off-service but remain typically non-intrusive.

If a measure of coil current is not available, a current sensor should be installed. For DC sensors the installation is generally off-service.

3.3.16 Drive Mechanism status

Mechanical issues comprise a large portion of field issues with switchgear. Naturally, there is a strong interest to develop and deploy condition monitoring methods to detect these issues before they become failures during operation. Historically, mechanical monitoring methods were invasive, requiring the switchgear to be taken out-of-service in order not only to install the devices, but also to make the measurements. New methods have been developed that allow users to assess the state of the switchgear while remaining in-service. Advances in signal processing techniques have enhanced the ability to interpret these measurements between a baseline (initial nominal operating characteristics) and periodic or continuous monitoring of the switchgear.

3.3.16.1 Motor Position and Torque

APPLICATION

Monitoring of motor position or torque is a commonly used technique to detect mechanical abnormalities of circuit breakers if it is directly driven by the motor [CIGRE_167_2000]. Motor drives can be used both for medium- and high-voltage applications, with a high-voltage circuit breaker application depicted in Figure 3-57.

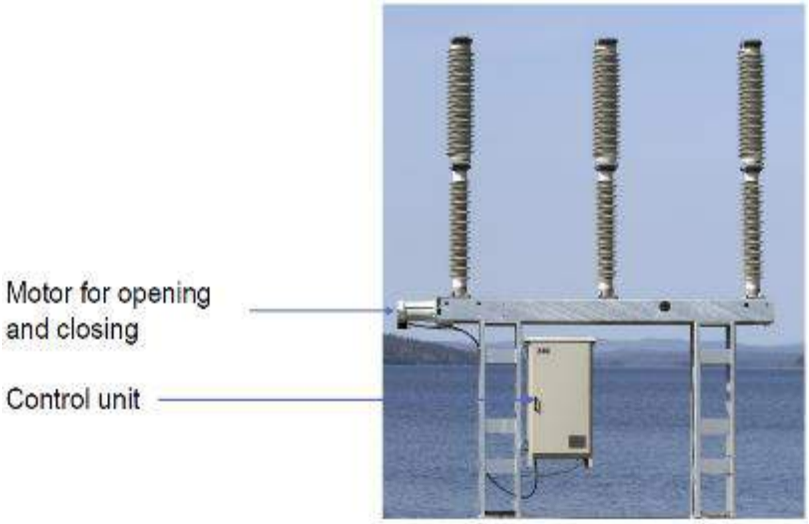


Figure 3-57: Actual installation of circuit breaker with motor drive [ABB2006]

MODE OF APPLICATION

Periodic Measurement	**Continuous Monitoring** ✔

THEORETICAL BACKGROUND

For switching devices with a motor directly driving it, overall operating time of the switch is the same as motor runtime. For high range applications, travel can be controlled and surveyed in real time by a microprocessor unit, thanks to position sensor feedback, motor current and voltage sensor feedback. The goal is then to stick to a preset ideal travel curve profile, all along the operation. For lower range applications, the motor is just operated in an open loop. However, in any case, the instantaneous current absorbed by the motor (thus, the torque) is a direct indication of the mechanical effort and can reveal abnormalities. This capability to measure the instantaneous effort is a major advantage over conventional spring, compressed air or hydraulic drives, regarding monitoring. Additionally, the local energy storage unit (capacitor bank, batteries…) can be monitored (time to charge, voltage).

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

Nowadays many modern electronic devices, including protection relays, have motor current or voltage measurement functions. Also, modern MV/HV circuit breakers normally have very small variation in motor operating characteristics measurable by motor current or voltage, therefore, users can detect deviation of measured data in a relatively accurate manner.

On the other hand, there are constraints for switching devices with the motor not directly driving the mechanism, i.e. spring charged type circuit breakers. In this case, motor motion or torque will not represent the state of the main current part of the circuit breakers, thus it is recommended users adopt another method like trip coil current monitoring.

3.3.16.2 Spring Stored Energy Status

APPLICATION

For motor charged spring type mechanism circuit breakers, the easiest way to recognize whether the status of the operation spring is ready or not is to see the commonly integrated stored energy indicator [IEEE1999a] on the device. While such can provide information whether the motor and the mechanisms are still functional, it does not signify a completely healthy mechanical system. In order to ensure reliability of the switching equipment, such as medium-voltage and high-voltage switchgear, it is also important to monitor soundness of the spring charging mechanisms.

MODE OF APPLICATION	Periodic Measurement	**Continuous Monitoring** ✔

THEORETICAL BACKGROUND

Spring Charge Quality Estimation Function

The spring charge quality estimation function calculates the spring charging time. The circuit breaker spring should be charged within a specified time. Long spring charging can be due to early motor failures as seen in the measurements or can be due to higher friction forces. A shorter recharging time can be due to a lower spring constant. Therefore, detecting long or small spring charging time indicates that it is time for circuit breaker maintenance. This diagnostic function is based on the quality scheme. Warning and alarm threshold times are set by the manufacturer who knows the expected times for each breaker (Figure 3-58). If the spring charging times drops in zones different from the normal ones, the quality of the breaker will decrease.

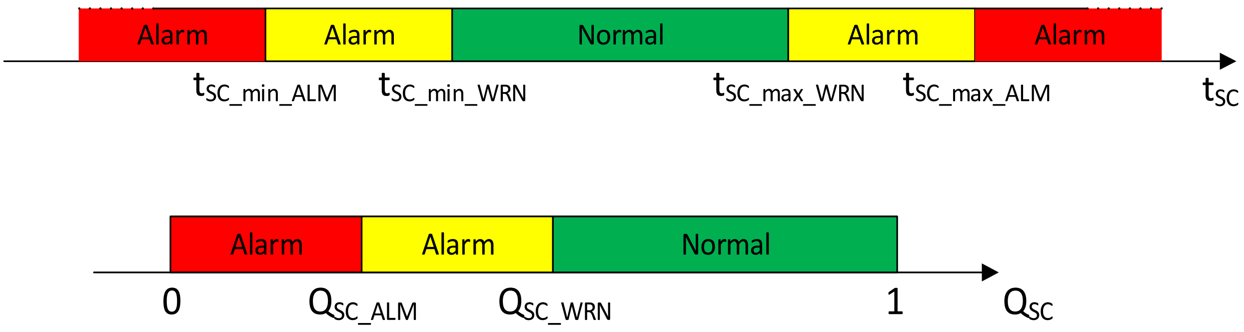


Figure 3-58: : Time- and quality-based warning and alarm thresholds [Saeli2012]

Fatal Attempt to Charge Function

The fatal attempt to charge calculates the occurrence of unexpected recharges of the spring. Due to the recharge mechanics, there might be a sudden slip-through which triggers a recharge operation. This failed attempt to charge can be detected in the following way: in normal operation the motor is started at a closing of the breaker and a sensor detects when the spring is completely charged. Therefore, an approach to track a slip-through is to check whether the sensor signals that the spring has been charged without any closing operation. Figure 3-59 shows this event.

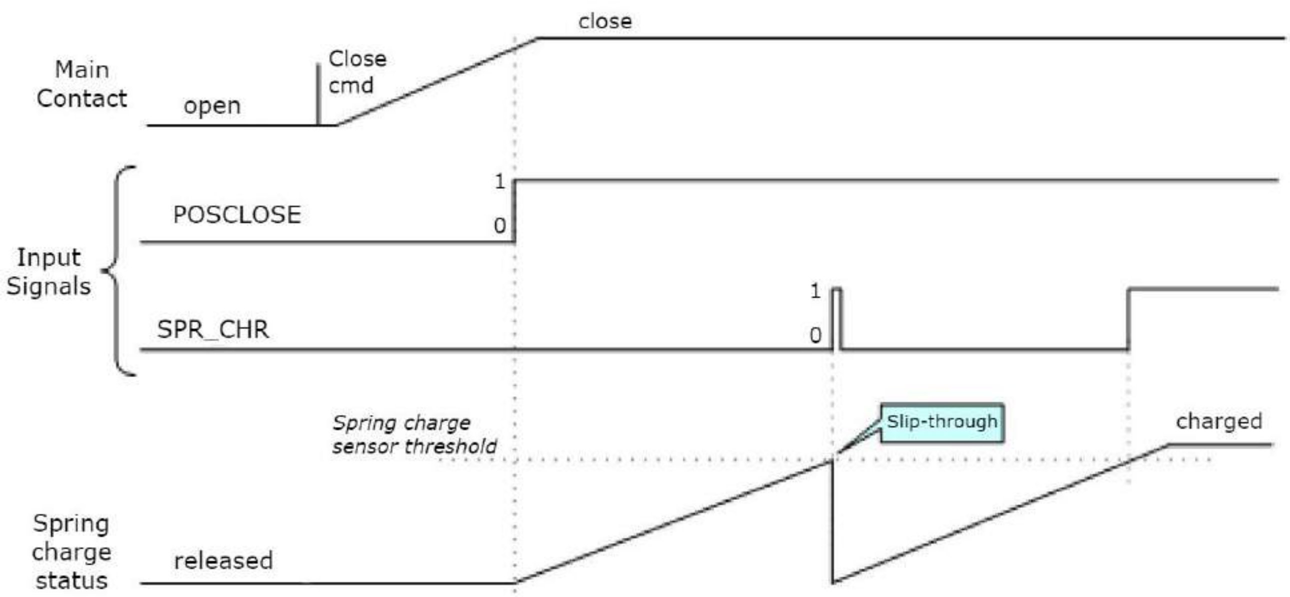


Figure 3-59: Fatal attempt to charge diagram [Saeli2012]

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

The circuit breaker should be integrated with a special relay, able to monitor and control the correct functionality of the device, as well as to perform auto-diagnostic functions relating to the spring stored energy status.

3.3.17 History of operation

The wear of contacts is a factor that influences directly the lifetime of a circuit breaker. It is widely accepted that contact erosion and nozzle ablation is a function of a number of parameters from which the most relevant ones are the total charge transferred through the main contacts and total energy accumulated over years of operation.

The information regarding wear and failure probability is of upmost importance to system operators and asset managers. In this subchapter three widely accepted and used methods are described and evaluated based on their merits.

3.3.17.1 I²T Recording

APPLICATION

Contact wear can be assessed by summarizing the arcing over the whole time of operation. It is not a direct measurement but is an indicator for the contact wear and widely used because of its ease of application.

MODE OF APPLICATION

Periodic Measurement	**Continuous Monitoring** ✔

THEORETICAL BACKGROUND

I²T represents the energy during switching (arcing) and goes in line with physical wear of the contacts. Monitoring the cumulative amount of arcing energy allows an estimation of contact wear and, in reverse, may indicate the remaining electrical life time of the apparatus. The wear depends approximately on the square of current amplitude multiplied by the time of arcing. Square of current amplitude is an approximation; the exponent can be more or less than two depending on the intensity of the arc. For simplicity an exponent of 2 is chosen as a typical average value.

It is only a rough approximation of the actual interrupter wear, especially if the start of the cumulation is more or less arbitrary and the equation itself ignores the design of the interrupter.

The recorded value always shows the accumulated value of arcing energy. For exact calculation, the duration of each arc also has to be known. While it is easy to measure in the laboratory, it is difficult to measure using typical CT and protection relays in the field. Therefore, average arc duration is assumed as a constant value and applied to all switching operations in a protection relay. Over the life time, all data are summarized, which results in an average value. The maximum permissible electrical wear of the interrupter is expressed by:

$$\sum n \times I^k = T$$

Equation 3-4

Where:

n is the number of switching operations (both normal and abnormal), I is the rms value of the current in kA, k an exponent on the order of 1.8 to 2 depending on the wear characteristic of the chamber and T the total permissible number of operations for that circuit breaker in particular. As an example, Figure 3-60 shows the maximum permissible electrical wear for an LTB HVCB of the 145kV voltage level.

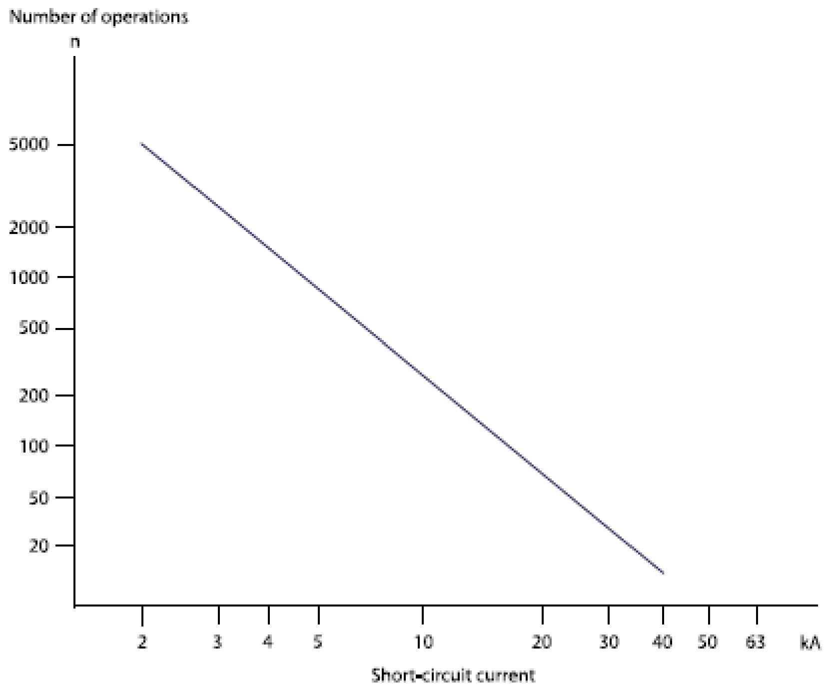


Figure 3-60: Maximum permissible electrical wear [ABB2013]

Digital protection relays or controller can easily calculate this value. It is state-of-the-art for modern protection relays to have this function. When reaching a threshold, sometimes called ageing factor K, an alarm or other status information will be sent out. The threshold as a certain percentage of the maximum value as well as the maximum value have to be set during commissioning.

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

It is an easy method to monitor for any relay or controller which measures primary current. Exact values of maximum value and previous life (in case the switch / breaker was not new when the relay / controller was commissioned) have to be entered, otherwise the warning signal will not be issued at the correct instant of time.

End of life prediction is unprecise. Whether it will still be able to break 100% of short circuit current, withstand 80% of test voltage or withstand full TRV cannot be determined with this information without a more elaborated assessment.

It is not an accurate diagnostic method and there are a number of uncertainties using this method:

1. Calculation is not very accurate and despite the averaging effect over lifetime it will never be an exact value.

- The exponent is not exactly two. due to manufacturers using different designs and the arc energy also depending on the kind of fault current
- the arc duration varies in reality while calculation assumes a constant (average) value
- some relays may only count fault interruptions. High load current interruptions also result in (very small) contact wear overall and the result may become less accurate for a higher ratio of load current switching to fault current switching

2. The "end of life" value when measured as I^2T is not exactly known. Manufacturers can assign this value based on experience, but it will still have tolerances.

Considering the fact that most circuit breakers operate during their life well below the possible number of fault interruptions, comparing the I^2T value to historical data will give a good indication that there is an issue when a circuit breaker approaches the end of life based on fault interruptions.

3.3.17.2 Number of fault operations

APPLICATION

Protection relays often have the option to count fault operations. This would count any trip operation initiated by a protection element and may be limited to certain fault types only.

As a function of the protection relay or control unit, it is not linked to any particular voltage range but is used in high and medium voltage devices.

MODE OF APPLICATION

Periodic Measurement	**Continuous Monitoring** ✔

THEORETICAL BACKGROUND

Every time the protection relay issues a trip signal, it will count this as a fault operation. It could be limited to certain fault types, i.e. to count overcurrent faults only but no over-/undervoltage faults. There might be different counters, i.e. (i) total number of fault operations, (ii) fault operations since last maintenance, (iii) fault operations within a pre-defined timeframe.

This information is often used to draw conclusions about the situation in the network, as it shows the frequency of fault situations. It may also be used to indicate the consumption of service life, but would need to be compared to other counters of this section.

DEGREE OF MATURITY ■■■■■■■

EASE OF USE AND CONSTRAINTS

Fault Operations counter is an integral part of protection relays. The reliability is very high.

It should also be mentioned that their primary task is to show fault activities in the network. This information on its own does not allow conclusions about life time of the circuit breaker. It always has to be seen in conjunction with the other counter readings described in this section.

Operations counter by protection relays have the disadvantage that they only count since the time of commissioning. Hence a certain number of operations might be missed if the switch has already operated before commissioning of the protection.

3.3.17.3 Mechanical Operations Counter

APPLICATION

Operations counters are typically factory-installed devices that count the number of mechanical operations of a circuit breaker over its lifetime (including commissioning and field operations). Although prudent to record and use this data as part of a fleet maintenance program, this condition monitoring method of counting the number of operations will not be discussed in detail in this brochure. Mechanical operations counters are widely deployed on both medium- and high-voltage equipment.

MODE OF APPLICATION

Periodic Measurement	**Continuous Monitoring** ✔

THEORETICAL BACKGROUND

The operating cycle (of a mechanical switching device) is a succession of operations from one position to another and back to the first position through all other positions, if any. As per IEC it is left open which, whether the operating cycle starts with OPEN or CLOSE.

Counting of operations is well established and proven for a long time. There are two fundamental ways to monitor the number of operations:

1. Most circuit breaker and switches have mechanical operations counters. Often mechanically linked, sometimes also linked by electrical or magnetic means.
2. Protection relays (controller) also count the number of operations. They monitor the signals from auxiliary switches and count the operations. There might be different counters, i.e. (i) total number of operations, (ii) operations since last maintenance, (iii) operations within a pre-defined timeframe.

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

Operations counter is an integral part of the circuit breaker or switch. The reliability is very high, especially for mechanical linked counters. Since it is an integral part of the circuit breaker and not a separate device, the counter will always monitor the total number of operations since manufacturing.

Visibility of the counter may be limited for a number of reasons: (i) location of the counter, (ii) size of the numbers, (iii) accessibility of the counter. It can make it difficult for daily use. However, during maintenance it is no issue to read the counter.

Mechanical counters are not readable by electronic means, they are meant to be visually read.

Operations counter of protection relays have the disadvantage that they only count since time of commissioning. Hence a certain number of operations might be missed if the switch has already operated before commissioning together with the protection relay i.e. during factory testing. Also in case of relay change for maintenance or upgrade reasons the counter may start at a wrong number. Some relays allow adjustment to the historical value, but not all. Finally, the accuracy also depends on the care during commissioning, whether this value is entered correctly or not.

3.3.18 Travel Recording

3.3.18.1 Dynamic Contact Travel

APPLICATION

The performance of the circuit breaker is highly dependent on the travel characteristics of the closing and opening operation. Designers of the high voltage circuit breakers identify these critical parameters for each type of the breaker during the development stage (contact closing speed, contact opening speed, contact overtravel). Since the travel characteristics of the CB contacts can provide great insight into the proper functioning of the gear, measuring and analyzing these values can provide excellent insight into the health of the equipment. Measurements that deviate from the manufacturer's tolerance can provide early indication of mechanical problems, so condition-based maintenance can be scheduled to investigate and repair. [Andrusca2013, Levi2011, Renaudin2015, Levi2013]

In order to perform these measurements online, the circuit breaker must be outfitted with travel transducers that report the instantaneous position of the contacts, or some other portion of the mechanism (Figure 3-61).

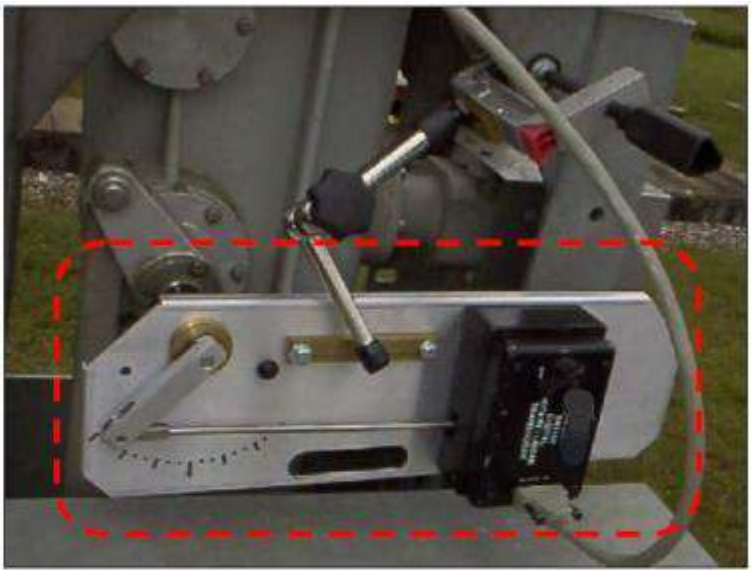


Figure 3-61: Motion transducer mounted on operating shaft of circuit breaker [Brown2012]

The contact travel analysis method can be applied to any circuit breaker with grounded mechanical components that track or reflect the instantaneous position of the contacts. The method has been deployed in both MV and HV environments, with various interrupting and dielectric media. Along with the position sensors, a data acquisition and analysis module is also needed to record, analyze, and interpret the results.

MODE OF APPLICATION

Periodic Measurement	✓	Continuous Monitoring

THEORETICAL BACKGROUND

Measurements of the instantaneous contact position are recorded and processed to extract several condition indicators. Delayed or slow speed of the contacts can cause malfunctions of the high current interrupting process. Most developing mechanical issues in a circuit breaker would be manifested in deviations from the expected travel characteristics. Output and measurement of the travel characteristics are shown as an example in Figure 3-62.

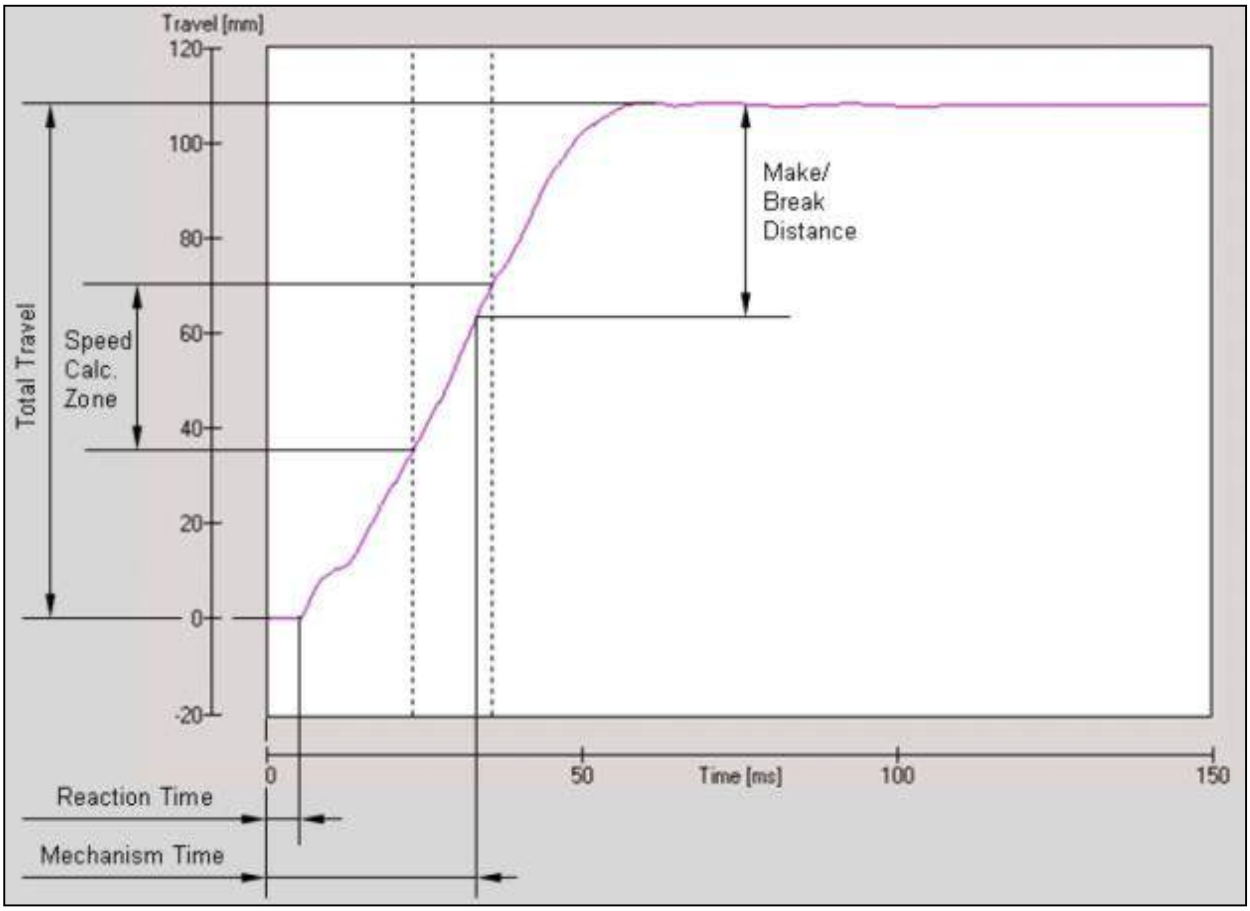


Figure 3-62: Example of dynamic contact travel measurement [Poeltl2011]

Another technique to detect abnormalities is to compare the travel characteristics to the reference curve, as described in the circuit breaker test standards. During different phases of the circuit breaker opening (acceleration, arcing, and damping), the percentage deviation between measured and reference travel curves can accentuate particular issues in the operating mechanism or drive train [Lalonde2015].
One particular factor affecting the travel characteristic is the electrodynamic forces acting on the contacts during a closing operation. In this case, deviations from the no-load travel characteristics should be accounted for in interpreting the dynamic travel data [Wang2007].

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

While dynamic contact travel analysis is a powerful tool to monitor the mechanical performance of the circuit breaker, it poses challenges in the installation of the sensors and interpretation of the data. In some cases, the sensor can be installed on a rotary component, and the linear travel of the contact can be inferred from the rotary position via a non-linear conversion factor. This may simplify the installation of the travel sensor. Once the sensors have been installed on the mechanism, collecting the measurements is simple, but determining if the data indicates an issue is dependent on a well-defined tolerance zone for the various key travel parameters. Typically, the manufacturer would need to provide this data specific to the circuit breaker or mechanism type. Some industry standards have suggested use cases for measuring contact travel using standardized communication and monitoring protocols [IEC2013]. Some utilities require circuit breaker manufacturers to install dynamic travel sensors during the assembly process, negating an in-service retrofit of the sensors in the field.

3.3.19 Coil current

The measurement of the coil current of closing and opening tripping devices is normal practice for routine tests since the starting point is defined as the time when the coil is energized.

3.3.19.1 Measurement and Analysis of coil current

APPLICATION

The analysis of the recorded current shape can provide useful information of the healthy status of the operating mechanism of the circuit breaker. The comparison with a reference fingerprint is a common practice particularly in continuous monitoring systems.

MODE OF APPLICATION

Detection & comparison with reference shape	**Periodic Measurement** ✔	**Continuous Monitoring** ✔

THEORETICAL BACKGROUND

Looking at the coil current diagram a typical behaviour can be identified.

Considering the most frequent case of DC powered closing and tripping coils, the principle diagram is shown in Figure 3-63.

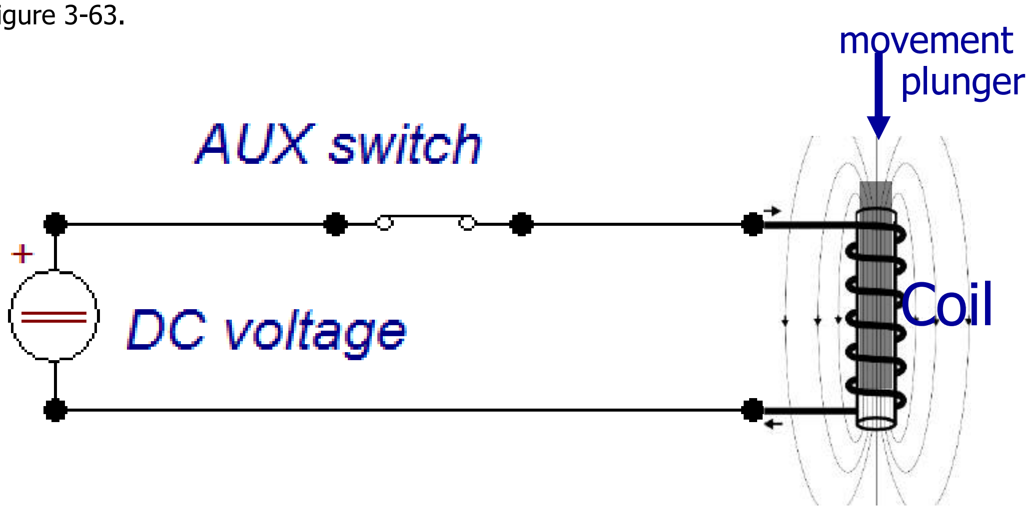


Figure 3-63: Principle diagram of a trip coil of a circuit breaker energized with DC voltage through circuit breaker auxiliary switch

The coil has a ferromagnetic steel plunger free to move in the middle. When a current flows through the winding, a magnetic field is generated. A force is acting on the ferromagnetic plunger trying to move it in a position where the magnetic reluctance is minimal.

The coil has a certain resistance defined by the wire dimensions and an inductance being a function of the winding and the ferromagnetic plunger material and position.

Without any movement, when a DC voltage is applied to the coil the current rises towards its steady state value $I = \frac{U}{R}$ with an exponential law having time constant of $\tau = \frac{L}{R}$

Being

- L the inductance of the coil
- R the resistance of the coil
- U the applied voltage.

The moving plunger changes the inductance and thus generates an electromotive force (e.m.f) which reduces the current flow. The faster the movement is, the higher the Electromotive force is and the bigger the influence on the current shape.

In Figure 3-64 a typical coil current recording is shown during an opening operation of a circuit breaker.

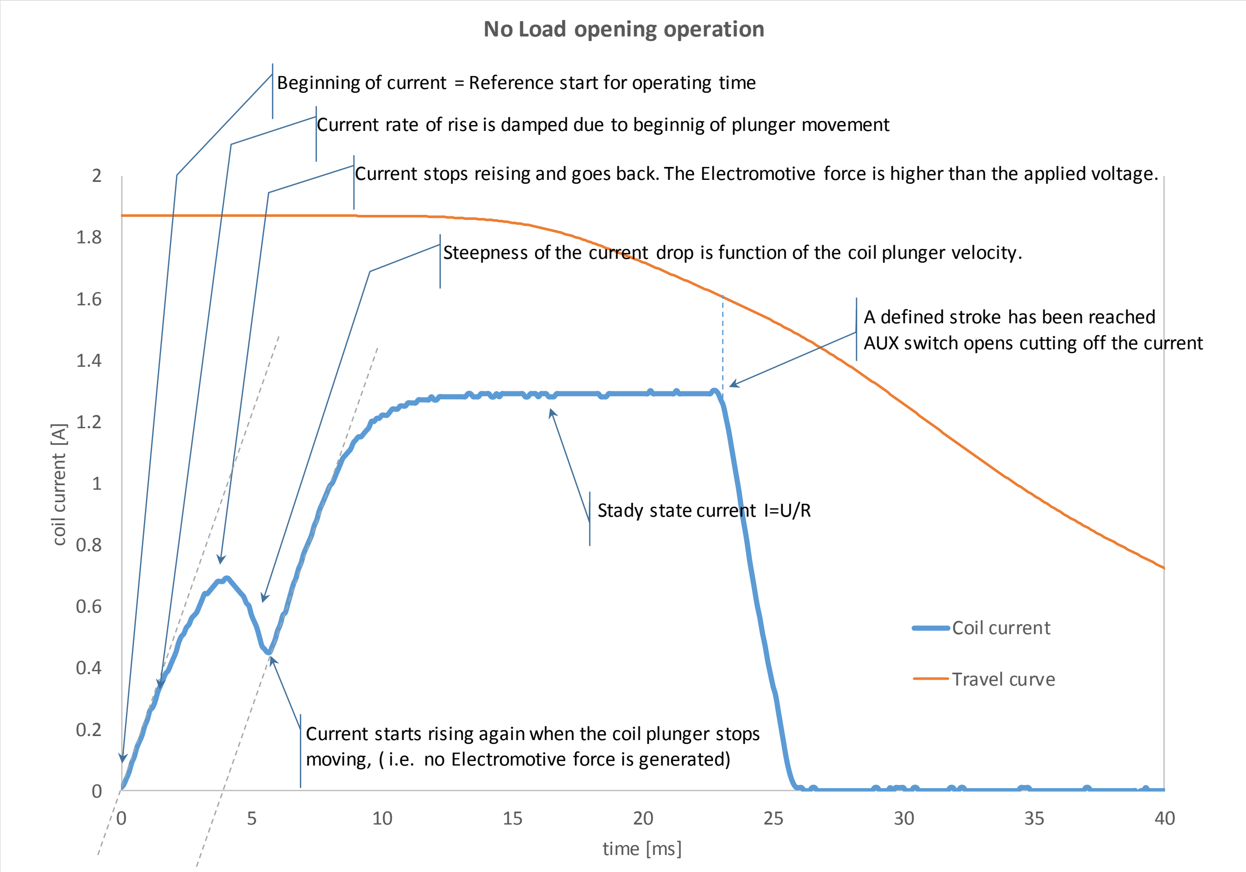


Figure 3-64: Recording of a coil current during an opening operation

At time zero the coil is energized with direct voltage U (77V in Figure 3-64).

This point defines the reference starting point of the circuit breaker opening time (the second one being the contact separation in the circuit breaker).

The current rises with a rate of rise $\frac{U}{L}$.

As soon as the plunger starts moving the rate of rise of the current is damped. Increasing the movement speed results in the current to stop rising and start dropping.

The steepness of the current drop is defined by the speed of the plunger. A flatter dropping in comparison to the normal one is an indication that the plunger is moving slower than normal. This is an indication of friction increase.

When the plunger movement reaches its end, the current starts rising again towards the steady state value $\frac{U}{R}$ with a quite similar rate of rise that it had at the beginning.

When the operating mechanism has reached a defined stroke, the auxiliary switches open cutting off the coil current.

An earlier or later start of the current cut off indicates a change of velocity of the operating mechanism.

DEGREE OF MATURITY

EASE OF USE AND CONSTRAINTS

- Analysis of the shape is a well known and settled diagnostic method for people dealing with circuit breakers.
- It requires a basic knowledge to be carried out properly.

Limit settings and use of comparison method with a reference finger print allows an automatic evaluation quite useful in the case of continuous monitoring.

3.4 SUMMARY

In this chapter, 55 condition assessment methods for switchgear were presented. The majority of these can be used for both MV and HV switchgear. The discussed methods were classified in three different categories: Primary Path, Mechanical and Control. While some of the methods have to be installed intrusively or minimally intrusively, all of the presented methods operate completely non-intrusively. In addition, the presented methods have been further categorized in their grid integrity as well as their degree of maturity. Many of the methods are very mature, however for example most of the methods that investigate the condition of the vacuum in a vacuum circuit breaker are still in the investigation phase.

4. APPLICATION OF CONDITION ASSESSMENT METHODS

4.1 INTRODUCTION

Having identified and documented a large number of non-intrusive diagnostic methods that could potentially improve maintenance and condition assessment practices in the power delivery industry, the JWG A3.32 was then interested in knowing how these methods are actually used and perceived by different utilities. Therefore, the WG decided to conduct an international survey on condition assessment of T&D switchgear. The questionnaire was developed using a specialized web tool, allowing users to conveniently answer the survey online (Figure 4-4). The survey could be filled in for three voltage levels; <38 kV, >38 to ≤170 kV and >170 kV. It was sent at the beginning of 2015 to hundreds of people with some relationship to the WG members.

Altogether, a total of 49 independent respondents coming from 18 different countries have answered the survey. When broken down across the different voltage classes, the number of completed surveys were 31 for <38 kV, 33 for >38 to ≤170 kV and 27 for >170 kV. The answers have been collected anonymously from February 2nd, 2015 to November 25th, 2016. The analyses and outcomes of the survey are presented in Section 4.2 and APPENDIX E provides full details of the survey questionnaire.

Among the objectives of the survey, we wanted to gather feedback, experience and future needs from utilities regarding condition assessment, and to better understand the context in which non-intrusive diagnostics are applied by utilities.

4.2 SURVEY RESULTS

At first, the respondent was asked to provide general information on its company profile (location, size, etc.) and detailed information on its circuit breaker fleet, such as voltage levels, number of units, technologies, etc. Then, for each category of circuit breaker, we asked which type of maintenance is usually applied:

TIME BASED PREVENTIVE MAINTENANCE (TBPM)

Maintenance activities are performed at fixed intervals of calendar time or according to a number of switching operations. Both procedures and schedules are usually based on manufacturers' recommendations or industry standards.

CONDITION BASED MAINTENANCE (CBM)

Incipient failures are usually corrected before they become an impact to the grid operation. Under this approach, information from diagnostic tests and monitoring systems are usually used to predict future failures.

RELIABILITY CENTERED MAINTENANCE (RCM)

Maintenance activities are specified and scheduled in accordance with the statistical failure rate and/or life expectancy of the equipment.

CORRECTIVE MAINTENANCE (CM)

Degraded equipment is only repaired and or replaced when the impact of the degradation on the grid operation becomes unacceptable. This approach is often called "run to failure".

From the long list of non-intrusive methods presented in the previous chapter, the respondent selected those presently used by its company. For each non-intrusive diagnostic method selected, the respondent was asked to specify how the method was actually employed by its company by giving, for example, its degree of maturity and frequency of utilization.

Furthermore, we wanted to know the respondent's perception of each selected diagnostic method regarding its ease of use and also the ease in analyzing the diagnostic results. Also, the respondent's general opinion was sought by asking the following three questions for each voltage level:

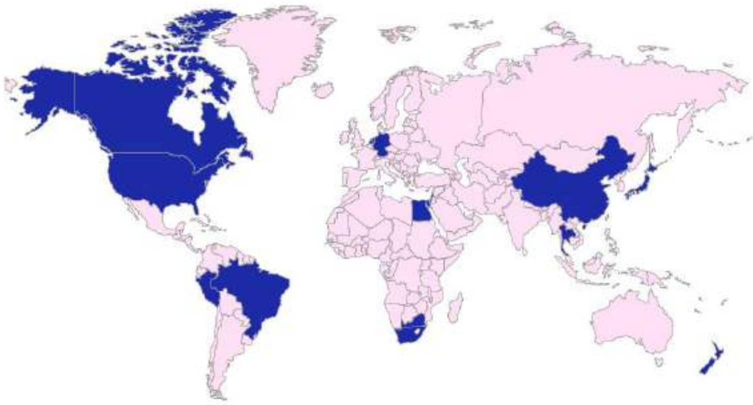
- How important is the cost advantage of using non-intrusive diagnostic techniques?

- How important is the advantage of performing tests on equipment remaining in service?
- How important is the advantage of performing tests on equipment without dismantling it?

In order to help our survey result analysis, the respondent was invited to qualify its answers with additional comments in a textbox appearing below each question.

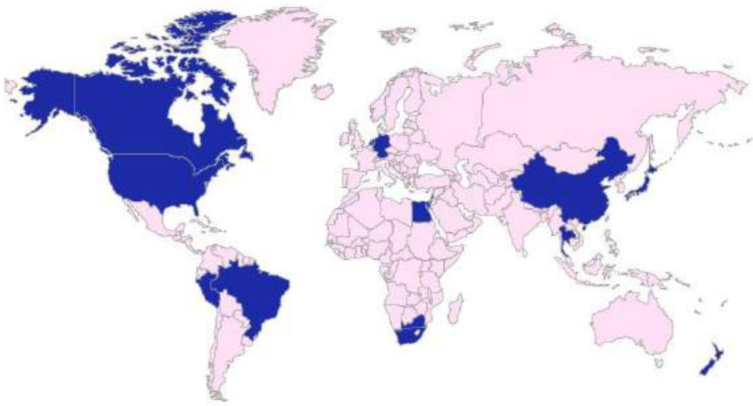
The structure of the survey is shown in Figure 4-4.

Figures 4-1 to 4-3 show the geographical spread of respondents for each of the three surveys.



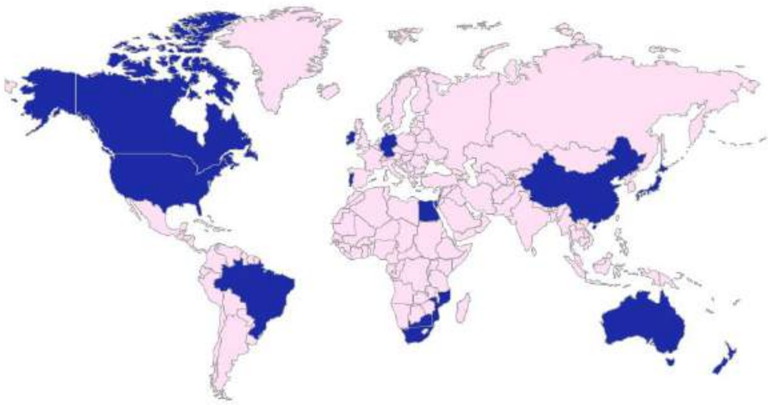
Countries (13)
Brazil
Canada
China
Egypt
Germany
Israel
Japan
Netherlands
New Zealand
South Africa
Thailand
USA

Figure 4-1: <38 kV Survey responses by country



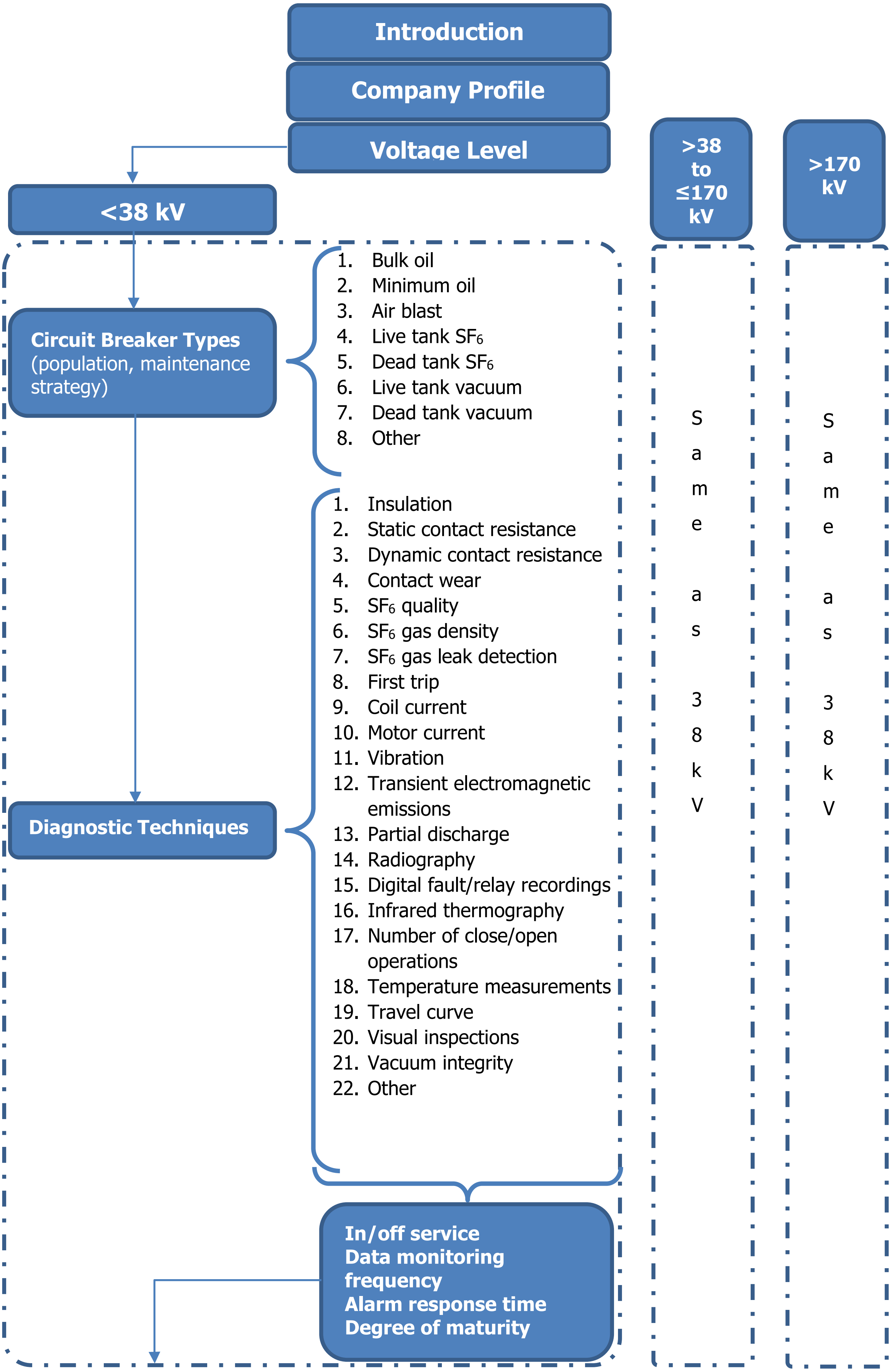
Countries (13)
Brazil
Canada
China
Egypt
Germany
Israel
Japan
Netherlands
New Zealand
South Africa
Thailand
USA

Figure 4-2: >38 to ≤170 kV Survey responses by country



Countries (15)
Australia
Brazil
Canada
China
Egypt
Germany
Hong Kong
Ireland
Israel
Japan
Mozambique
New Zealand
Portugal
South Africa
USA

Figure 4-3: >170 kV Survey responses by country


Introduction
Company Profile
Voltage Level
<38 kV
>38 to ≤170 kV
>170 kV
Circuit Breaker Types (population, maintenance strategy)
1. Bulk oil
2. Minimum oil
3. Air blast
4. Live tank SF6
5. Dead tank SF6
6. Live tank vacuum
7. Dead tank vacuum
8. Other
Diagnostic Techniques
1. Insulation
2. Static contact resistance
3. Dynamic contact resistance
4. Contact wear
5. SF6 quality
6. SF6 gas density
7. SF6 gas leak detection
8. First trip
9. Coil current
10. Motor current
11. Vibration
12. Transient electromagnetic emissions
13. Partial discharge
14. Radiography
15. Digital fault/relay recordings
16. Infrared thermography
17. Number of close/open operations
18. Temperature measurements
19. Travel curve
20. Visual inspections
21. Vacuum integrity
22. Other
In/off service
Data monitoring frequency
Alarm response time
Degree of maturity
Same as 38kV
Same as 38kV

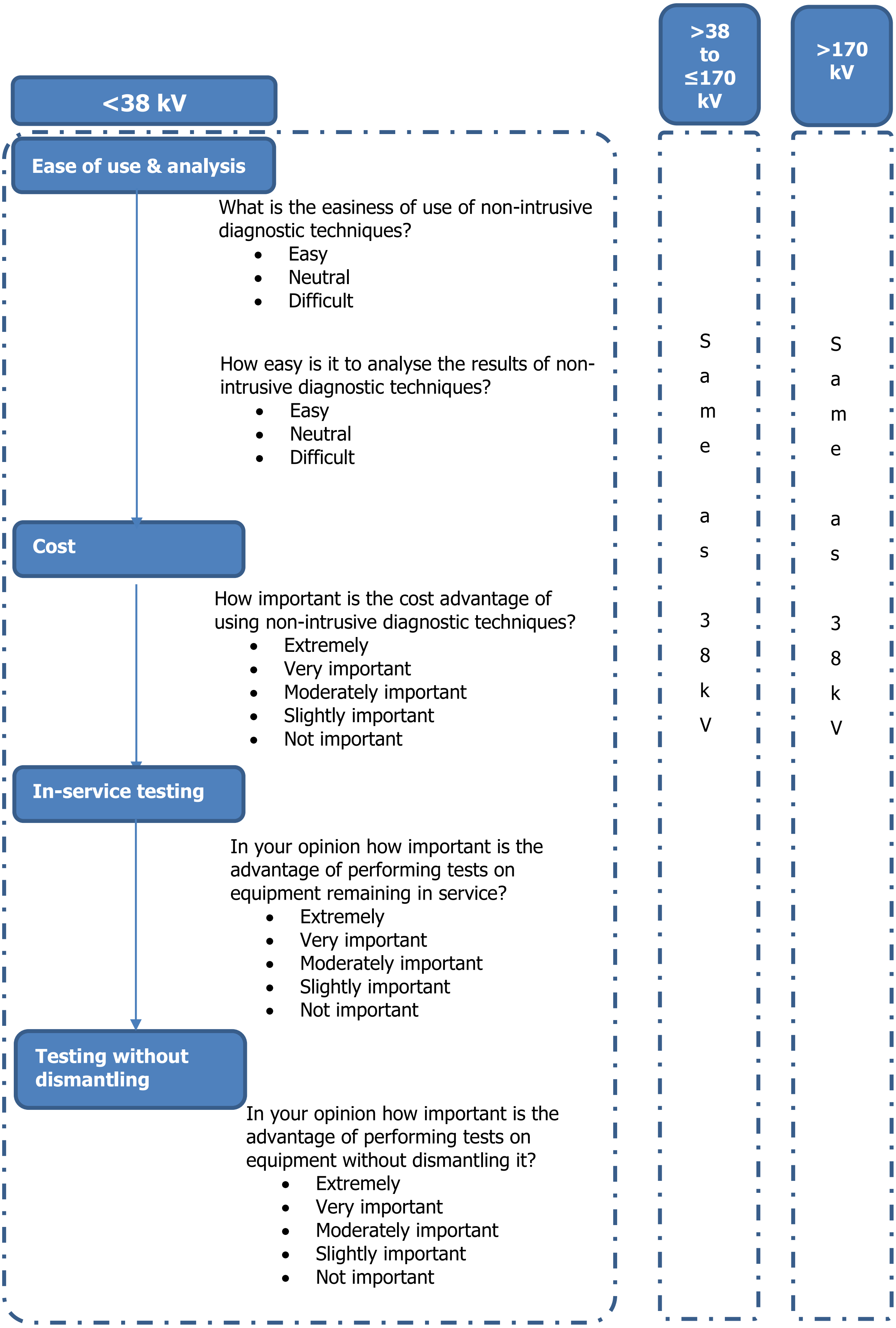


Figure 4-4: Survey structure

Figure 4-5 & Figure 4-6 respectively, show the in-service and off-service diagnostic techniques for each voltage class from the survey and the percentage of respondents who are using each technique. The most popular techniques are also ranked highest in ease of use. Infrared thermography, visual inspections and number of Close/Open operations techniques were used by more than 50% of respondents across the three voltage classes. In the >170 kV class, SF_6 density also ranked above 50%.

The less used in-service techniques such as contact wear, vacuum integrity, coil & motor current analysis were all more widely used as an off-service task. The three least used techniques were transient electromagnetic emissions, vibration analysis and radiography. Transient electromagnetic emissions is an in-service technique only and was not used by any respondents for the >38 to ≤170 kV class. It ranked as either neutral or difficult in ease of use and ease of analysis. Vibration analysis is used across all voltage classes but with less than 10% of all respondents using it. Ease of use and analysis was ranked either easy or neutral. Lastly radiography was used in both the <38 kV and >170 kV classes and ranked as either neutral or difficult to use and analyse.

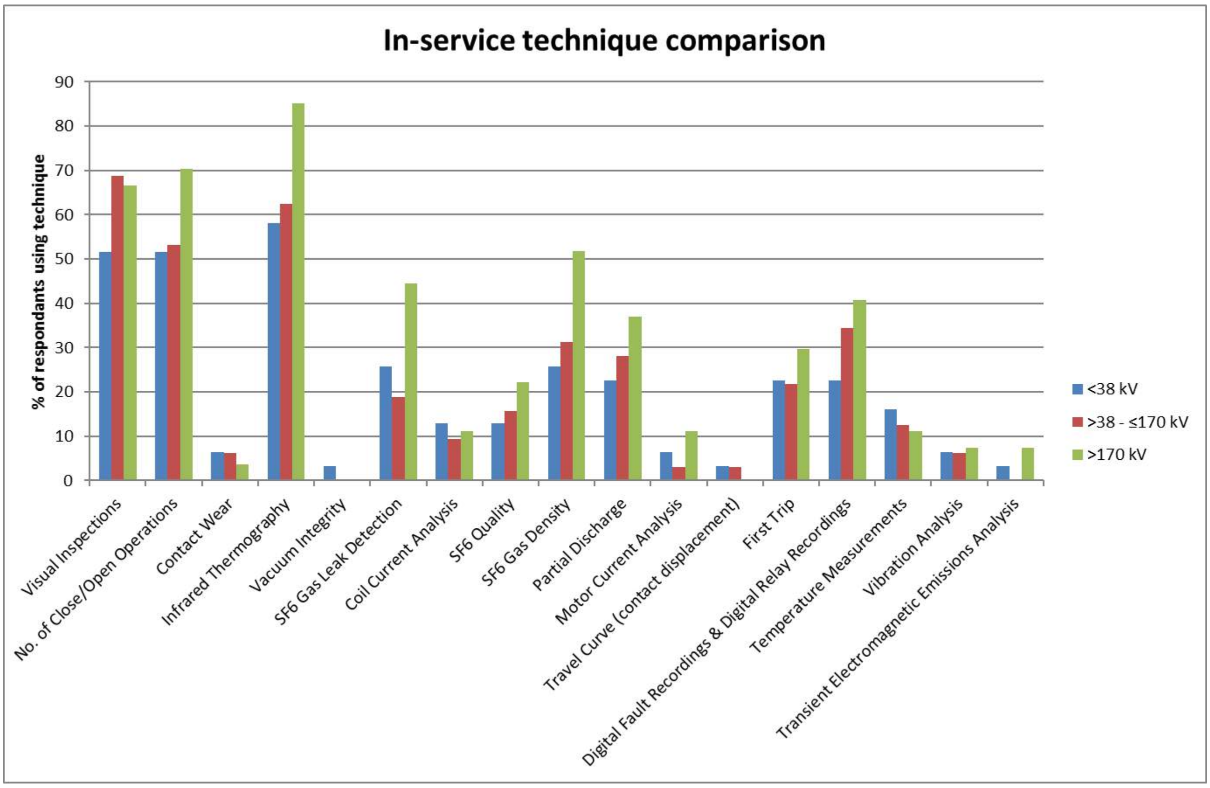


Figure 4-5: All respondent's in-service techniques

In the off-service category techniques such as static contact resistance, insulation test and travel curves, were used in the main by 50% of respondents however they were less popular in the <38 kV class. Again, these techniques ranked high in the easey of use and analyse categories. SF_6 gas quality measurements were far more popular in the both the >38 to ≤170 kV & >170 kV class. This could be attributed to one respondents comment for the <38 kV class - ***"SF_6 quality testing is not typically done as the interrupters are sealed with low volumes of gas."***

One other technique, which is being used by respondents but was not listed in the survey form, is minimum voltage trip/close testing.

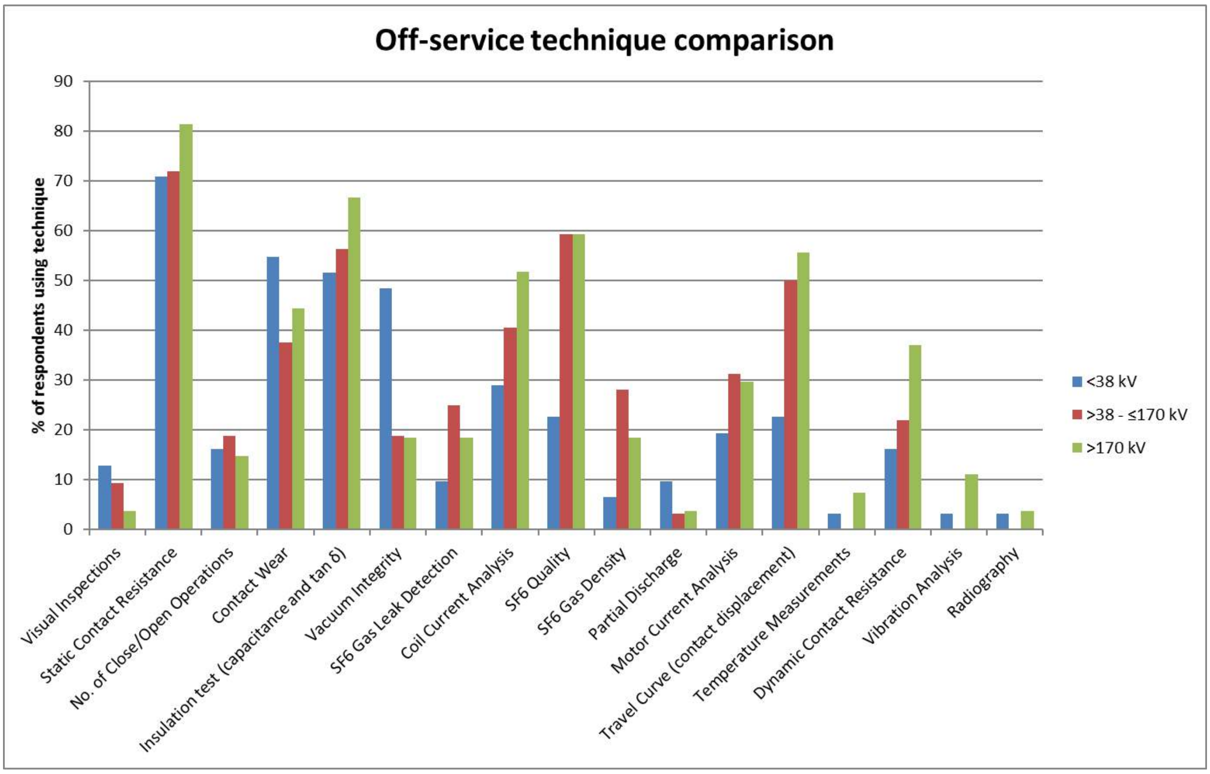


Figure 4-6: All respondent's off-service techniques

Figure 4-7 shows the distribution of the switchgear types by voltage class. For the higher voltage classes the mix is predominently between dead tank and live tank SF_6. For <38 kV the mix is spread across a number of different types with metal clad being the most popular.

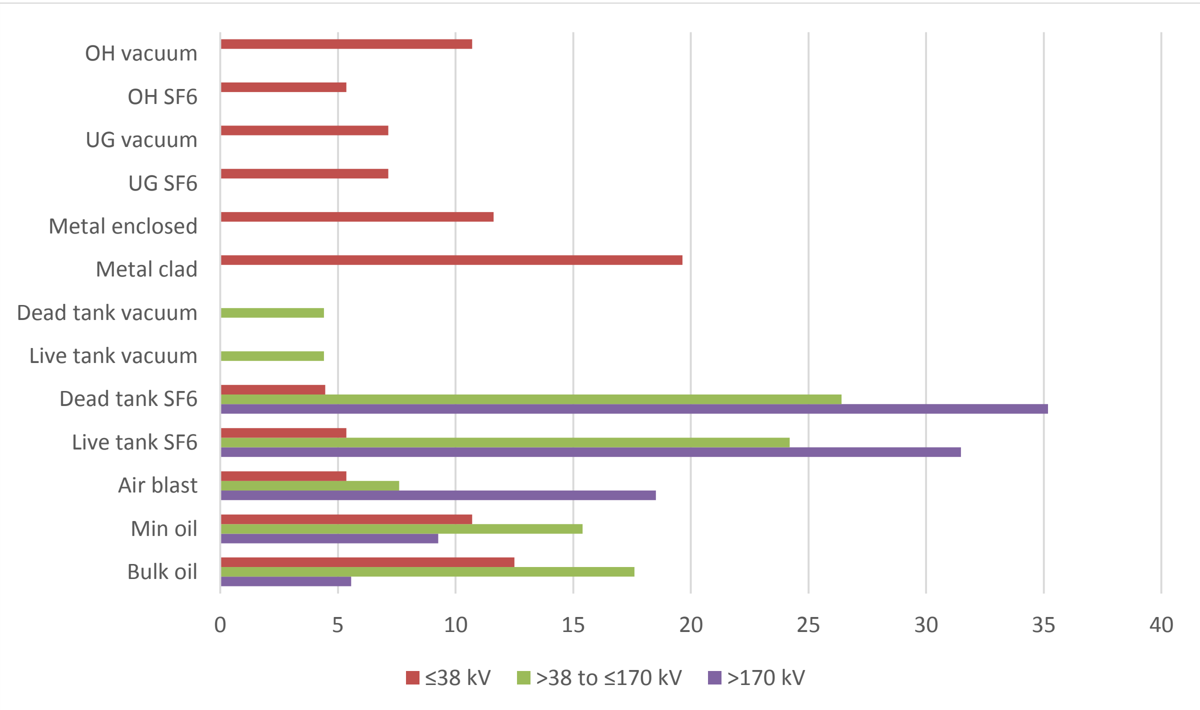


Figure 4-7: Switchgear types per voltage class

As stated above the techniques that were either difficult to use or analyse generally were the least popular. Table 4-1 below shows these techniques for each voltage class along with the techniques found to be difficult to use and analyse. For the <38 kV class there was a difference in the techniques which were difficult to use versus difficult to analyse. For the other two voltage classes, the same techniques were found to be both difficult to use and difficult to analyse.

Table 4-1: Difficult to use and difficult to analyse methods by voltage class

Voltage	Ease of use – Difficult	Ease of analysis – Difficult
<38 kV	Off-service contact wear, in-service SF_6 leak detection	Tan δ
>38 to ≤170 kV	Partial discharge	Partial discharge
>170 kV	Dynamic contact resistance	Dynamic contact resistance

Table 4-2 below shows techniques which were found to be easy to use and easy to analyse. As with the previous findings, there was consistency across the >38 to ≤170 kV & >170 kV classes. For the <38 kV class, the infrared technique was found to be either easy (50%) or neutral (44%) with regard to ease of analysis.

Table 4-2: Easy to use and easy to analyse methods by voltage class

Voltage	Ease of use – Easy	Ease of analysis – Easy
<38 kV	Static contact resistance, Infrared, No of CO operations, Visual inspection	Static contact resistance, No of CO operations, Visual inspection
>38 to ≤170 kV	Static contact resistance, SF_6 density, Infrared, No of CO operations, Visual inspection	Static contact resistance, SF_6 density, Infrared, No of CO operations, Visual inspection
>170 kV	Static contact resistance, SF_6 density, Infrared, No of CO operations, Visual inspection	Static contact resistance, SF_6 density, Infrared, No of CO operations, Visual inspection

To gain some insight on the importance of non intrusive conduction we asked questions A, B and C (below). The results were as expected and are shown in Figures 4-8 to 4-10.

A) How important is the cost advantage of using non-intrusive diagnostic techniques?

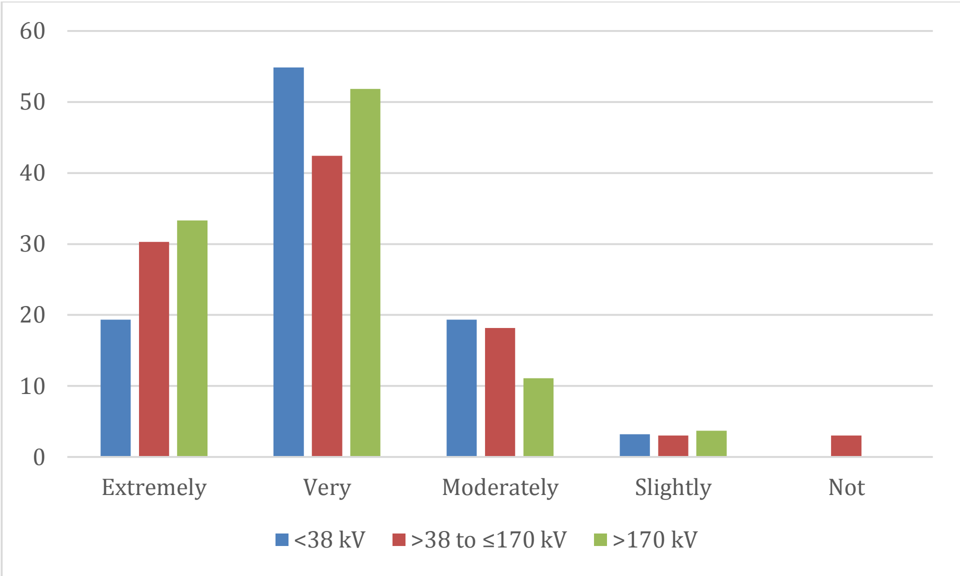


Figure 4-8: Importance of the cost advantage of using non-intrusive diagnostic techniques

B) In your opinion how important is the advantage of performing tests on equipment without dismantling it?

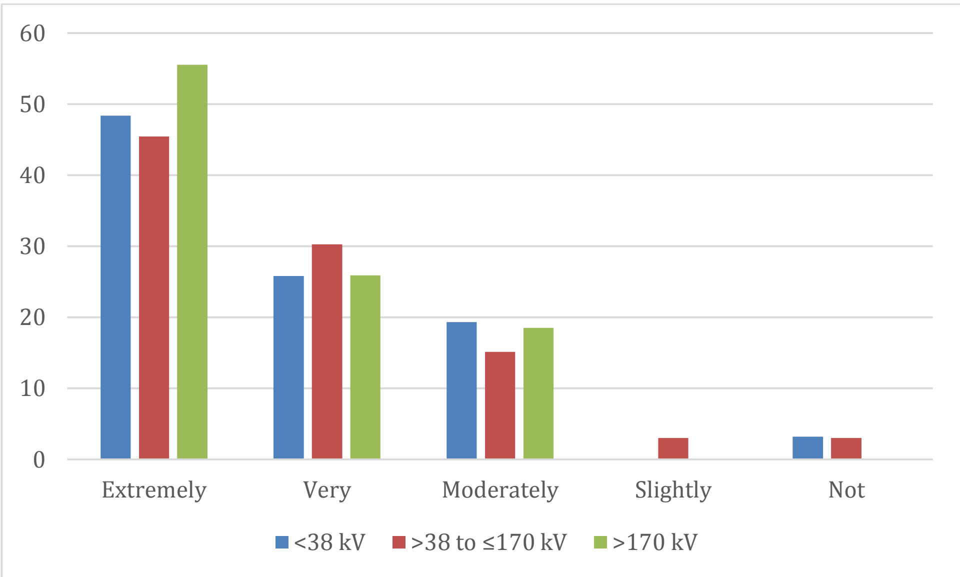


Figure 4-9: Importance of the advantage of performing tests on equipment without dismantling it

C) In your opinion how important is the advantage of performing tests on equipment remaining in service?

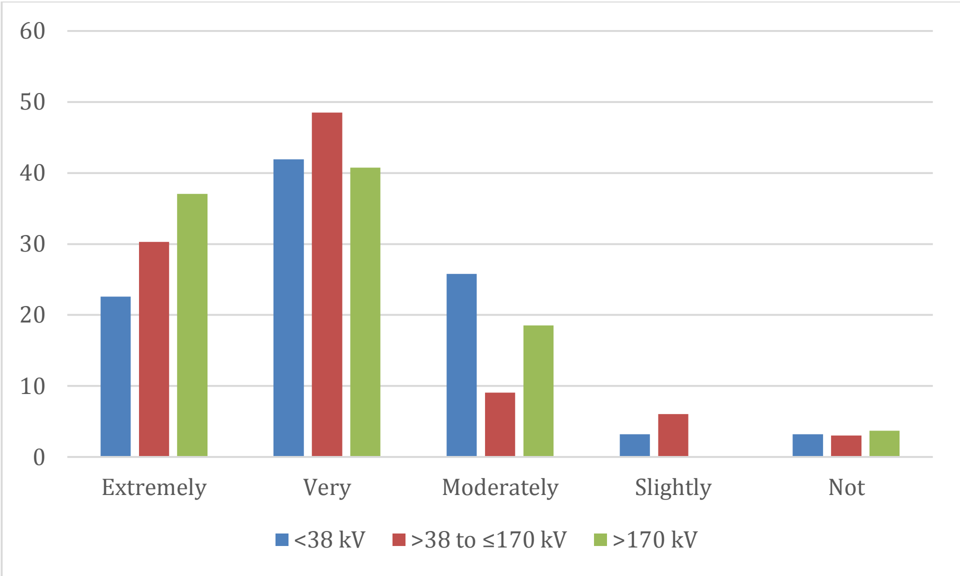


Figure 4-10: Importance of the advantage of performing tests on equipment remaining in service

As expected by the working group, the responses to the questions concerning costs, importance of not dismantling the equipment and that the equipment remains in service were either regarded as very or extremely important. Figure 4-8 to Figure 4-10 show how the respondents answer these three questions. The authors of this document believe that as the techniques become less expensive and easier to use, they will become more common place.

4.3 SELECTED CASE STUDIES

Case studies presented in this chapter are extracted from the literature review conducted by the JWG and from personal experience of WG members.

Condition assessment methods introduced in previous chapter may be applied in different contexts and for several different reasons. The main situations where such methods could be required include:

- Maintenance
- Investigation of failures
- End-of-life assessment

Case studies were selected in order to highlight the value and usefulness of applying non-intrusive methods in different situations. They also show how such methods can be applied by users. In this section, different strategies are presented, like applying a combination of non-intrusive methods to improve the CB condition assessment. In some others case studies, diagnostic methods are applied in progressive steps, starting with the most non-intrusive method that can be applied cheaply and easily. Then, after discovering a suspicious functioning or a bad condition of the CB, the investigation can progress towards intrusive methods. Such a diagnostic process is illustrated in Figure 4-11.

Some case studies also provide some ideas on how to analyse results obtained from non-intrusive diagnostics, which are often indirect measurements, without any acceptance criteria. The analyses include comparison between poles of the same breaker, trending analysis over a long period of time, etc.

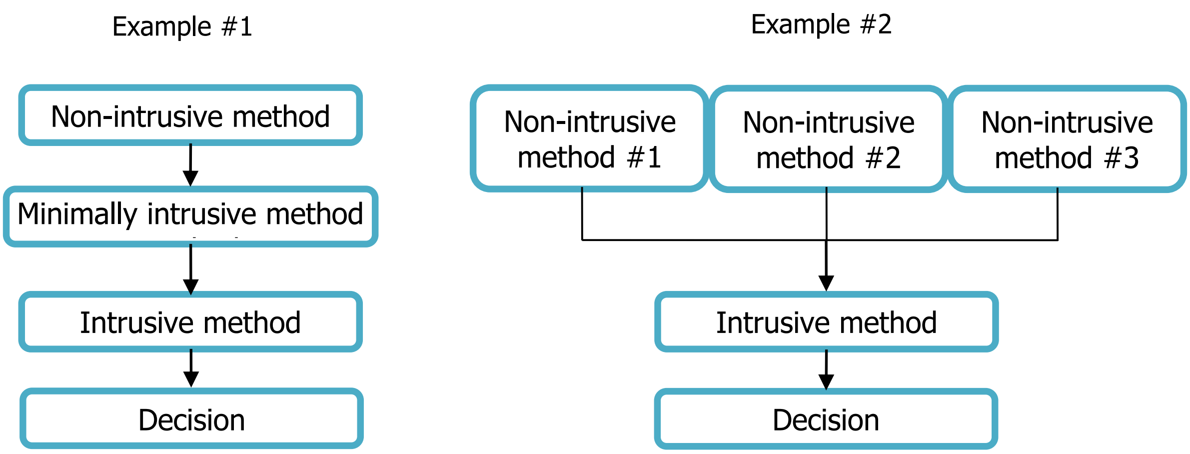


Figure 4-11: Example of diagnostic process in progressive step

4.3.1 Main Contact Motion Measurements

Measurement of contact motion with a transducer mounted on the operating mechanism is a well-established diagnostic test widely used on several types of circuit breakers. This method is known for providing good indications on the circuit breaker mechanism condition. However, some factors may complicate the analysis of motion curves:

- Unavailability of acceptance criteria
- Type and position of the transducer
- Lack of knowledge on the mechanical design
- The unknown relationship between the linear contact motion and the rotation

Typical condition indicators for motion measurement are (See Figure 3-62):

- Total Travel
- Speed Calculation Zone
- Make / Break Distance
- Reaction Time
- Mechanism time

Nevertheless, such criteria are not always provided by the manufacturer or known by the users. On the other hand, these criteria are only applicable for one moving point. If for a practical reason a transducer is mounted away from this point, a correspondence function should be applied, but this latter is not always available.

In the following example [Lalonde2015], motion test results at commissioning are used as reference for a 330 kV SF_6 circuit breaker without acceptance criteria. During routine maintenance tests, rotary motion curves were compared with the reference curve in three distinct zones (Figure 4-12). As the percentage of deviation for phase C motion in zone 3 (damping) differs considerably from A and B, it was decided to do a visual inspection of the opening dashpot accessible from the top of the operating mechanism, where obvious oil leaks have been found (Figure 4-13).

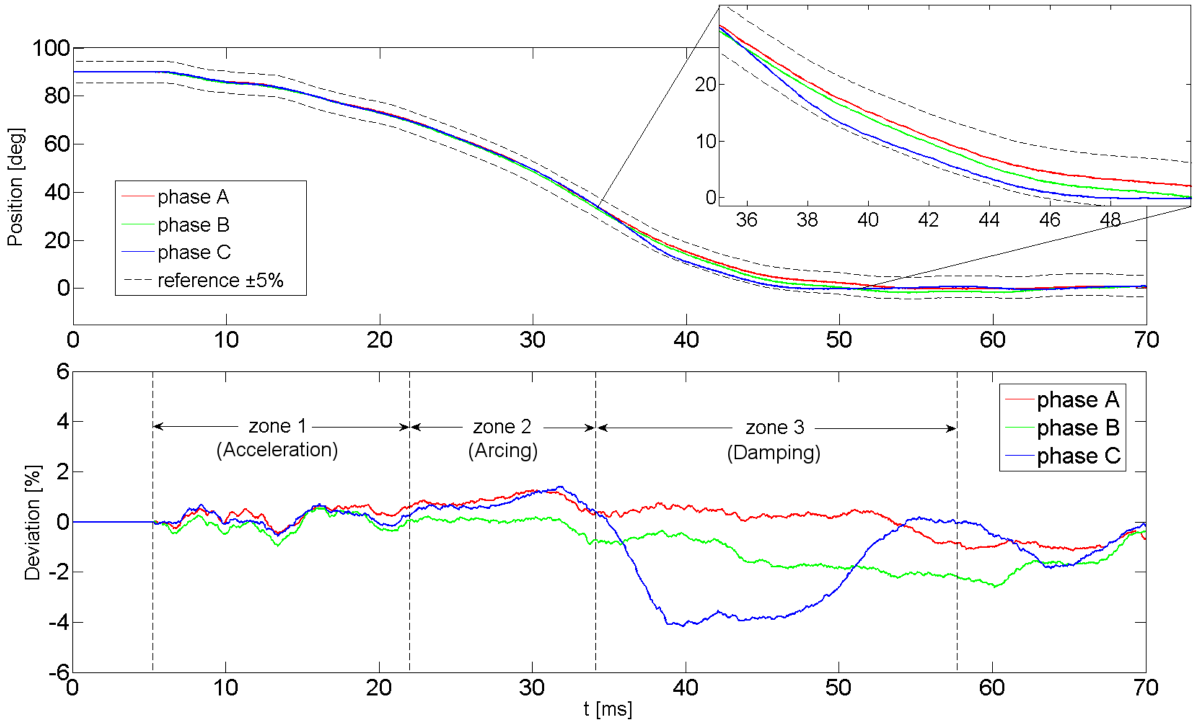


Figure 4-12: Deviation by zone between the reference curve and each phase of the tested HVCB [Lalonde2015]

Figure 4-13: Oil leak detected on the opening dashpot, phase C [Lalonde2015]

Motion measurements have also been successfully applied in the continuous monitoring mode. An excessively long reaction time has been discovered for one of the poles of a 550 kV dead-tank breaker [Poeltl2011].

4.3.2 SF_6 Density Monitoring

A decrease of the SF_6 density due to a gas leak in a circuit breaker directly affects its dielectric withstand and, consequently, its current interruption capabilities. The SF_6 gas leak is also of major concern for the environment due the very high global-warming potential of SF_6, which is 23,900 times greater than that of carbon dioxide (CO_2); it is also very persistent in the atmosphere with a lifetime of 3,200 years [Blackman2006].

SF_6 CBs are usually equipped with gas density switch triggering alarms when the gas density falls below predefined levels. These systems are usually not considered as a condition monitoring system because they do not allow for the early detection of a SF_6 leak before a low pressure alarm is raised. The gas density function is generally available on most on-line monitoring systems that measure simultaneously the gas pressure and temperature (Section 3.3.1.1).

Over the last two decades, a few gas leak detection surveys have been conducted by some electrical utilities on SF_6 circuit breakers. As a first example, an Australian utility gathered density data from one thousand CBs installed between 1970 and 2013 [Cheetham2014]. As shown in Figure 4-14, the leak rate significantly increases after ten years of service for every voltage level. In another study in the United States, a survey revealed that up to 23 percent of CBs were identified as leaking for a particular year of manufacture (Figure 4-15).

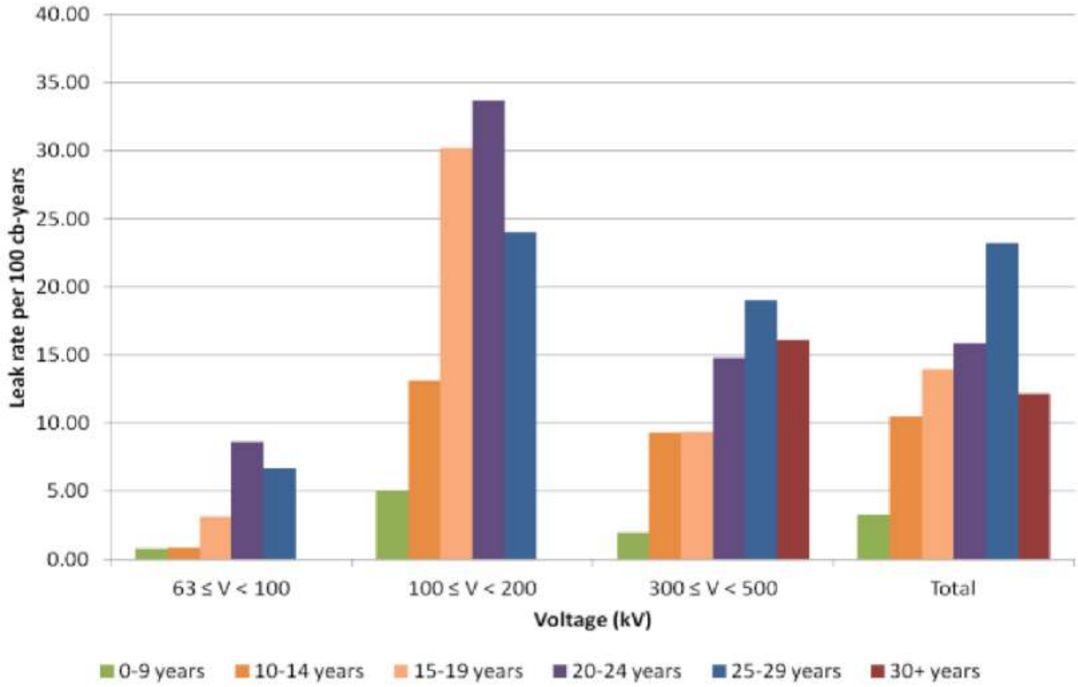


Figure 4-14: Proportion of leaking CBs from a population of 1000 CBs in Australia [Cheetham2014]

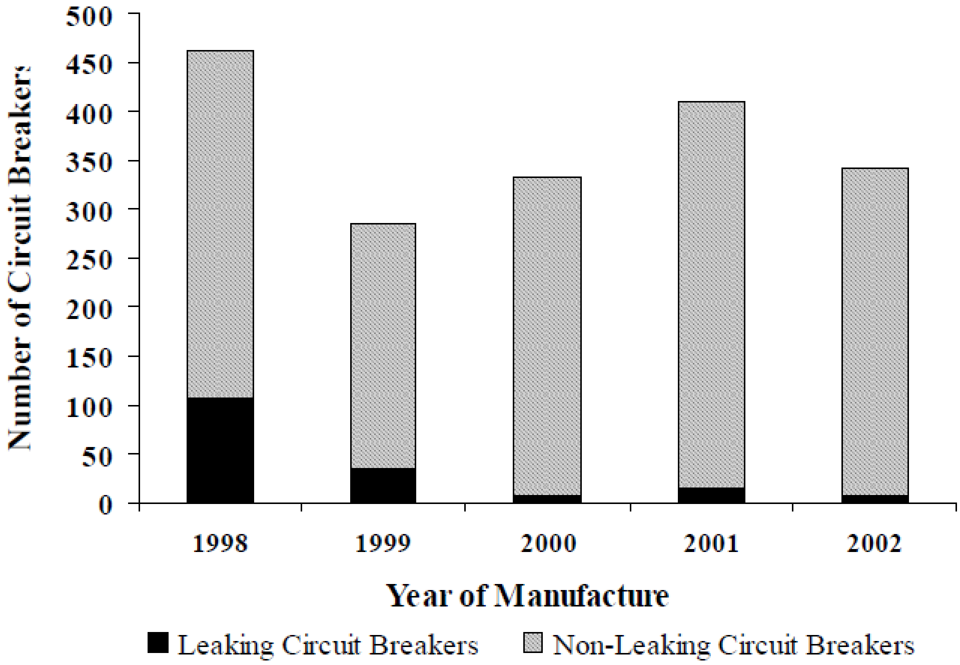


Figure 4-15: Proportion of leaking CBs of a population of CBs manufactured between 1998 et 2002 in the United States [Blackman2006]

For circuit breakers with a known history of leaks, such as the CBs manufactured 1998 in Figure 4-15, it should be considered to perform a targeted density monitoring by retrofitting density monitoring equipment such as presented in [Cheetham2014]. Two types of transducers commercially available can be retrofitted for monitoring:

- pressure and internal SF_6 gas temperature to derive density by applying the Beattie-Bridgeman equation of state;
- quartz oscillating principle to directly measure density (relationship between dynamic viscosity and density of a specific gas at a specific temperature);

In a Croatian utility, it was proposed to collect and deliver SF_6 gas sensor data over a wireless sensor network. This turned out to be a convenient way to automate older high voltage substations without requiring expensive and intrusive retrofits [Sostaric2011].

Another approach to detect gas leaks non-intrusively is the infrared imaging technology performed with a laser camera (Figure 4-16). This allows for a periodic inspection without installing sensors on the CB. In [Keith2000], the efficiency of the method has been proved by testing 460 CBs within four months. 9% of the population of CBs was found with detectable leaks. A major advantage of this method over conventional density measurements is its ability to identify rapidly the cause of the leak (fittings, bushing seals, welds, etc.) while the CB remains in service.

Figure 4-16: Gas leak inspection of a SF_6 CB with laser system [Keith2000]

4.3.3 Digital Fault Recorder and Protective Relay Data Analysis

Current secondary system devices used in energy transmission and distribution systems have a possibility to acquire time records of currents and voltages with sampling frequencies more than 1 kHz. These devices can be:

1. Fault recorders – Devices specialized for acquisition of fault situation time records. A typical triggering condition is a signal from a protection relay. But it is possible to extend the triggering condition. It can be triggered for example from normal operation of the circuit breaker, overvoltage and overcurrent.
2. Digital protection relays – Theses devices are specialized for detection of faults, but it is possible to configure theses device similarly to fault recorders. In fact the fault recorder is a protection relay without the protection logic inside.

3. Special monitoring systems – Some monitoring systems of the equipment are equipped with time record acquisition system, such as a transformer monitoring system.
4. Special devices – Currently it is possible to install special devices for time records acquisition. These systems usually have a higher sampling frequency and the triggering condition can also be extended. I.e. the triggering signal can be generated any time the difference between real measurement and expected sine wave exceeds a threshold value.

The transient analysis during normal and fault situations can identify incorrect behavior of the equipment. I.e. restrike during no load opening operations can identify problems in the arcing chamber of the circuit breaker. Moreover exploring the condition of the arcing chamber is very complicated and expensive and is not a non-intrusive diagnostic method.

In case the utility uses digital protection relays, it is not necessary to install any additional devices. The only thing necessary to be done is to set the protection relays to be able to acquire transient time records from normal CB operation, collect these records and analyze them.

"AROPO software is permanently analyzing records of transients data from 350 fault recorders from the whole transmission system in the Czech Republic." … CEPS (transmission system operator in the Czech Republic) and has been in operation since year 2007. [Svancar2015].

Figure 4-17 shows data captured from a fault recorder. The data usually comes in Comtrade format with sampling frequency of 1 kHz. The length of one record is approximately 5 seconds. The following values are received from the fault recorder:

- 8 analog values
    - 4 voltages (UL1, UL2, UL3, U0)
    - 4 currents (IL1, IL2, IL3, I0)
- N digital values
    - Protection data (tripping, …)
    - Equipment data (coil signals)
- Timestamp

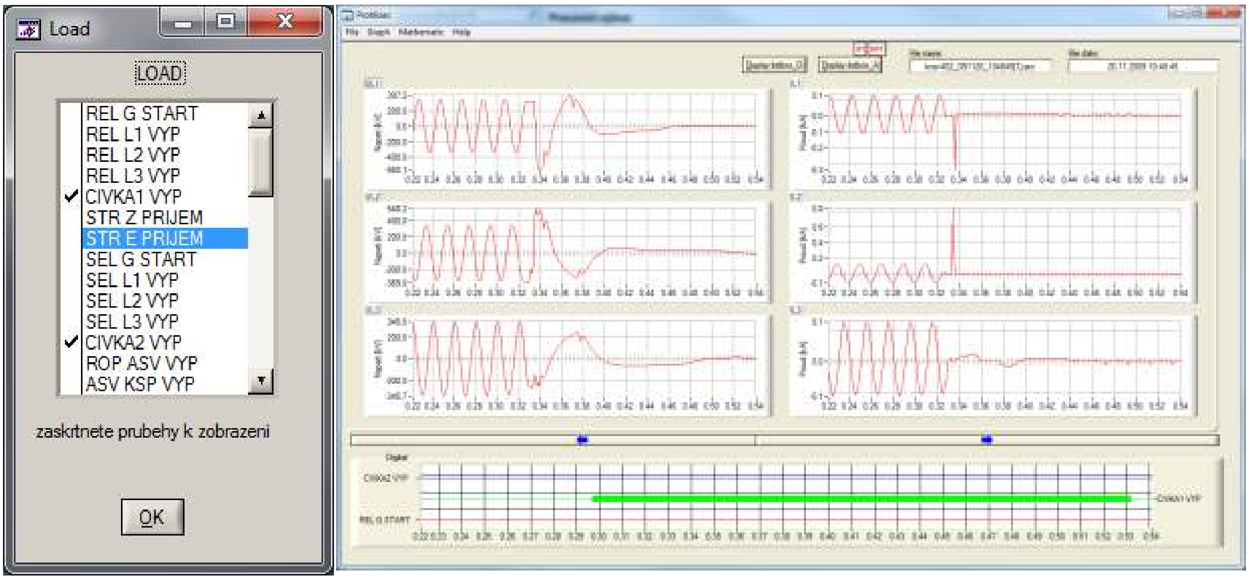


Figure 4-17: Example of data received from fault recorder

Currently, there are systems capable of performing time record analysis on the market. As an example, ACMart is an asset management system capable of performing condition based maintenance (CBM) or even risk based maintenance (RBM). The system continuously collects data about loading of the equipment, major and minor failures and calculates the health index of the equipment. ACMart also calculates the criticality of each particular equipment. From the criticality and health indices it automatically calculates a risk index. There are also some prediction algorithms for risk index prediction. Data from the event recorders can also be used to detect specific failure phenomena. Examples of the types of phenomena detectable include restrikes, re-ignition and time pole discrepancies.

At American Transmission Company (ATC) in Wisconsin, USA, protection engineers, maintenance managers, the control center operations team, and Electric Power Research Institute (EPRI) researchers have collaborated to demonstrate relay programming and alarming capability. The programming and timing alarms have already served to identify a specific fleet of 69 kV circuit breakers with persistent slow-trip issues. Existing relays can thus detect slow first trips of circuit breakers after those breakers have been standing idle for months or years in normal service [Desai2012].

4.3.4 Monitoring in Controlled Switching Devices

During the operation shown in Figure 4-18, the CSD controlled the opening operation but the programmed arcing time was close to the minimum arcing time window of the circuit breaker, leading to re-ignition in phases A and C. The application was reactor switching (neutral grounded) with a self-blast SF_6 circuit breaker.

It is evident that current zeros sequence are no more equally shifted by 60°.

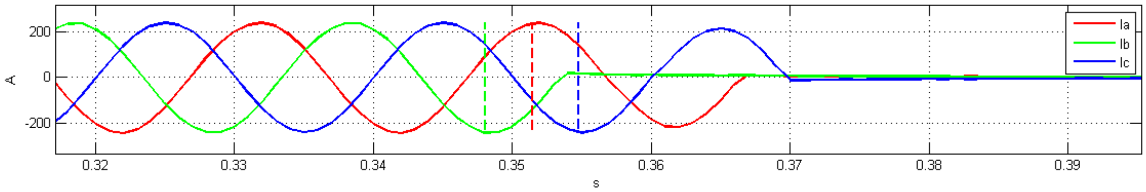


Figure 4-18: Example of re-ignition detected by CSD (red and blue phase) during reactor opening. Contact separation instants marked with dotted lines

Figure 4-19 represents an example of a power transformer switching ON operation (no load), during spread sequence. First phase to close (B, green) was perfectly closed at voltage peak, without any inrush (transformer demagnetized). Subsequent phases closed too early, leading to moderate inrush.

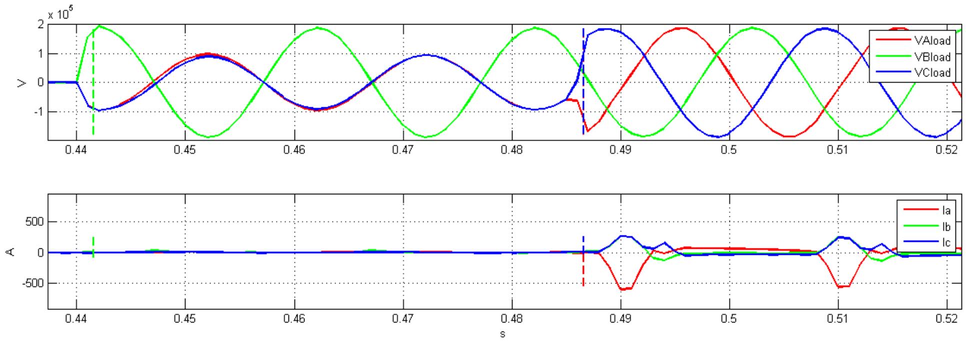


Figure 4-19: Example of record in CSD (power transformer closing: load voltages & currents). Red and blue phase too early by ~1.5ms due to setting error. Two dead periods between first (green) phase and remaining ones.

Figure 4-20 represents an example of a power transformer switching ON operation (no load), during narrow sequence. Because of residual flux presence in the transformer core and making times not being accurate, high inrush was observed, leading to a high level of harmonics in the system voltage.

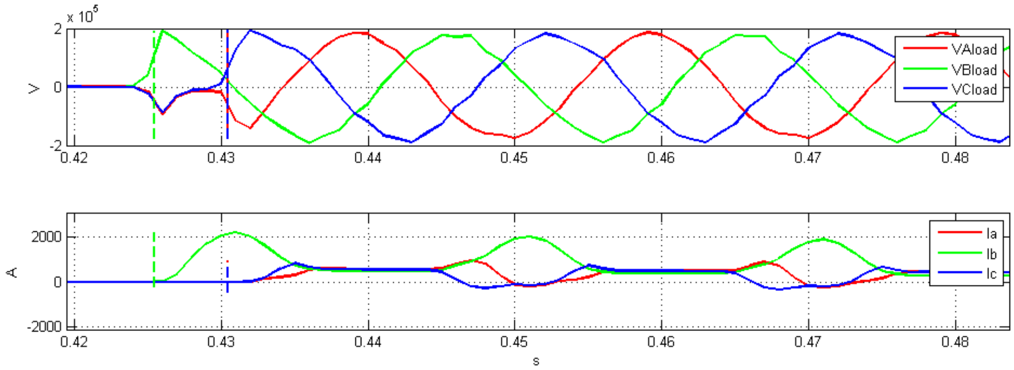


Figure 4-20: Example of record in CSD (power transformer closing: load voltages & currents). Making times not accurate leading to high inrush (2300A) and 11% of total harmonic level.

All of these waveforms have been extracted from CSD record files.

In some cases, when an unexpected and more radical CB timing change occurred, they played an essential role in helping to identify the root cause of the mis-operation.

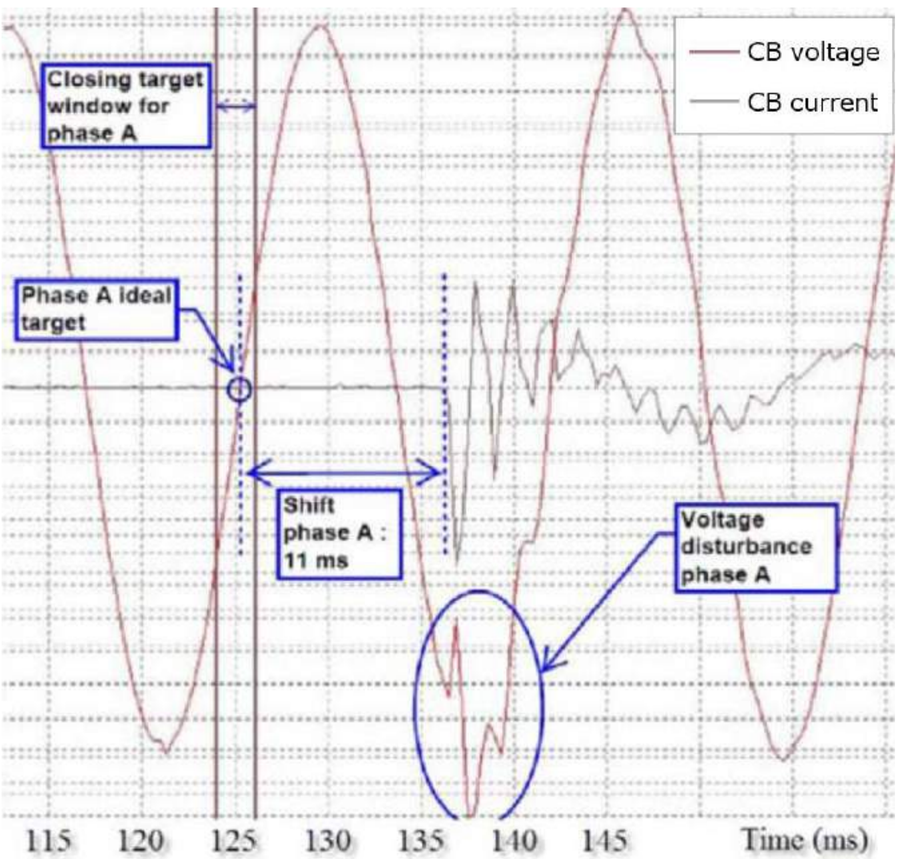


Figure 4-21: Closing time drift detected with CSD data

Before carrying out a major and intrusive maintenance task, a portable timing system was temporarily installed on the de-energized CB, and three displacement sensors were connected. With the three closing coils thus connected to the timing system, a closing order was generated. The results shown in Figure 4-21 validated that phase A was in fact faulty, and confirmed that the CB should remain out of service until properly repaired.

This case shows a valuable practice where the investigation is made in three steps, beginning with a non-intrusive method, namely the monitoring functions of the CSD. This first step allowed detection of a suspicious mechanical functioning of the circuit-breaker. However, the diagnostic at that stage was not considered strong enough to take the decision of dismantling the circuit-breaker. Therefore, it was decided to continue the investigation with an offline timing test that confirmed the mechanical drift observed by the CSD. Finally, when the mechanical problem has been confirmed by the timing test results, the decision was made to dismantle and repair the CB.

4.3.5 Experience with Vibration Analysis

As can be seen from the experience reported in [Landry2008a], major mechanical abnormalities can be discovered by applying the vibration analysis method. Even mechanical problems arising from the moving parts in the interrupting chambers of live-tank CBs can be detected if accelerometers are mounted on chambers while the CB is out of service.

An analysis based on an improved DTW algorithm allowed detecting abnormal vibration patterns on two SF_6 CBs. Then, intrusive visual inspections confirmed that these abnormal patterns were caused by severe mechanical defects. In the first case, a distorted transmission shaft was found in the operating mechanism. In the second, loosening of the auxiliary closing contact (closing resistors) was discovered in a 315-kV CB equipped with a hydraulic drive mechanism.

Figure 4-22: Loosening of the auxiliary closing contact of 315-kV CB [Landry2008a]

The vibration analysis method has also been tested in continuous monitoring mode [Hoidalen2005]. Three spring-operated SF_6 CBs in normal service have been monitored during three years. Over a thousand vibration patterns have been analyzed. According to this study, two of the three monitored CBs were operating well. However, the vibration patterns found on the third CB showed systematic deviation in the vibration patterns two operations before the CB failed to open on command. After the visual inspection inside the CB cabinet, a part responsible for stopping the rotational movement of the main shaft was found to be broken.

In both case studies reported in [Hoidalen2005] and [Landry2008a], it is explained that a problem is suspected when the deviation between the measured pattern and a reference pattern exceeds a predefined alarm level. The validity of the analysis also depends upon the availability and the quality of the reference vibration pattern that could be recorded at CB commissioning. In the absence of such a reference curve based on a new CB, it is nevertheless possible to compare vibration patterns between phases of the same CB or between CBs of the same family.

The main challenge in vibration analysis is to avoid false alarms, which can discourage users to use such a method. Alarms may be triggered by amplitude, time, or frequency deviation between the measured and the reference pattern. Alarm levels should thus be finely adjusted. For example, if vibration analysis is used in a continuous monitoring mode, electrical noise generated by the switching operation may be induced in the measurement cables and may disturb the measurement.

It is clear that important mechanical defects can be found by this method before a major failure occurs. However, the vibration analyses required for detecting such defects may be quite complex and may lead to wrong interpretations. As depicted in these case studies, natural deviations of the CB and external electrical disturbances in the substation environment may require the user to adjust alarms levels. It is also explained in [Landry2008a] that the positioning of accelerometers on the CB is crucial to obtain valid vibration patterns. Hence, the vibration analysis method is generally considered as reserved for advanced users. If the method is carefully applied, it has been demonstrated that such a method may be a powerful non-intrusive tool for detecting mechanical defects.

4.3.6 Experience with Power Factor Testing

The purpose of the power factor (tan deltaGST) tests is to detect the presence of contamination and/or deterioration of the circuit breaker's insulating system, which will allow corrective actions to be taken to ensure the integrity of the circuit breaker. This is done by measuring the insulation's dielectric-loss and capacitance and calculating the power-factor. The increase of the dielectric-loss, and consequently the power factor, is representative of an increase in contamination and/or deterioration of the insulating system and can detect a number of problems including:

- Moisture contamination resulting from leaks or incomplete cleaning and drying
- Deterioration of line-to-ground and contact-grading capacitors
- Surface contamination of weather sheds
- Deterioration of insulating components such as operating rods, interrupters, interrupter supports caused by corrosive arc by-products
- Internal corona damage of the same components listed above as a result of voids within the insulation system
- Impurities, contamination and/or particles within the SF_6 gas

In the following example [Nowak2011], an ABB Type 72-PM-31-20, manufactured in 1996, along with two others, same vintage and type were being moved from one location to another. Before placing them in service, the three circuit breakers were power factor tested. One of the UST readings was much higher than the other phases on all three circuit breakers. The following results are for the problem breaker (Table 4-3):

Table 4-3: Power factor test after moving circuit breaker

Bushing	Test Mode	Current(uA)	Watts-Loss	% Power-Factor
1	GST-Ground	727	0.018	0.25
2	GST-Ground	531	0.028	0.53
3	GST-Ground	724	0.017	0.23
4	GST-Ground	528	0.011	0.21
5	GST-Ground	732	0.013	0.18
6	GST-Ground	528	0.008	0.15
1 – 2	UST	20	0.008	N/A
3 – 4	UST	16	0.001	N/A
5 – 6	UST	20	0.000	N/A

A comparison of all three circuit breakers UST results can be seen in Table 4-4 below:

Table 4-4: Comparison of power factor test of circuit breakers

Breaker #	Bushing	Test Mode	Current(uA)	Watts-Loss
1	1 – 2	UST	20	0.008
1	3 – 4	UST	16	0.001
1	5 – 6	UST	20	0.000
2	1 – 2	UST	21	0.001
2	3 – 4	UST	18	0.001
2	5 – 6	UST	20	0.001
3	1 – 2	UST	21	0.001
3	3 – 4	UST	17	0.001
3	5 – 6	UST	20	0.001

The client opened the pole for the first breaker and discovered clear signs of a flash-over. Photos of the damage can be seen in Figure 4-23.

Figure 4-23: Signs of flashover on a circuit breaker

Table 4-5: Final results for circuit breaker after replacing pole

Bushing	Test Mode	Current(uA)	Watts-Loss	% Power-Factor
1	GST-Ground	729	0.006	0.08
2	GST-Ground	531	0.006	0.11
3	GST-Ground	727	0.006	0.08
4	GST-Ground	533	0.010	0.19
5	GST-Ground	734	0.006	0.08
6	GST-Ground	530	0.005	0.09
1 – 2	UST	18	0.000	N/A
3 – 4	UST	15	0.000	N/A
5 – 6	UST	18	0.000	N/A

This example shows the benefit of comparing data with similar apparatus. In this case, comparing the results with the same type and vintage breakers showed the high watts results for the UST test and high power factor on the ground tests for the same phase.

4.3.7 Experience with Coil Current Analysis

Profiling of coil currents can be performed both in-service and off-service. The in-service testing is more commonly known as "First Trip" testing. The parameters measured by both techniques are very similar with the in-service method estimating the main contact opening time whereas the off-service method gives a more accurate result owing to the fact the test kit is directly connected to the high voltage terminals.

The parameters measured and analysed are as follows:

- Trip or close coil currents
- Main contact opening time

- Auxiliary contact timing
- Battery voltage

Figure 4-24 below shows a typical trip coil profile with each stage of the mechanism identified.

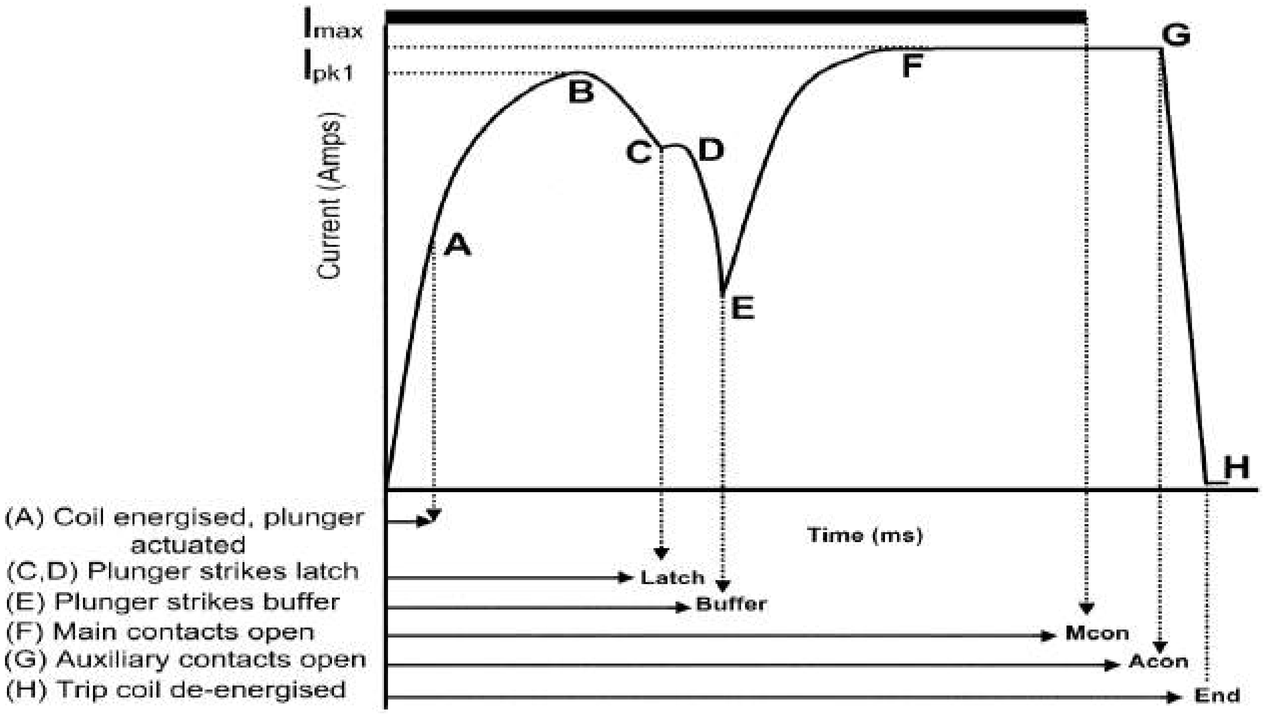


Figure 4-24: Typical coil profile

From the data captured the following problems can be identified:

- Mechanism lubrication issues
- Coil damage/deterioration
- Auxiliary contact issues – burned or dirty, loose connections
- Battery and/or charger problems
- Cable sizing

Measuring a circuit breaker's control circuit during operation to provide an insight into the condition of the operating mechanism has been around for many years. A utility company [Speed2000] implemented a testing program on 15 kV, 25 kV and 69 kV circuit breakers as these classes historically caused the most problems. After a six month period they were successful in identifying breakers in failure mode, they then broadened the program to include 138 kV circuit breakers. The data was utilized to prioritize maintenance, document healthy breakers and identify "bad actors".

The problems found during this testing were failed operating mechanism lubrication, damaged coils, dirty auxiliary switches, loose connections, battery or charger problems, improper control cable sizing and tailsprings out of adjustment.

The Kelman P1 Analyser was used to record the profiles. TXU Electric created some general guidelines as to what they should expect for a normal operation, these were:

- Main Contacts < 50ms on trip shot (3 cycle breaker)
- Main Contacts < 200ms on close shot
- Breaker off latch < 17ms (1 cycle for a 3 cycle breaker)
- Voltage drop < 10%

The next step was to check if the second trip was faster than the first, see Figure 4-25, this was regarded as a good indicator of faulty lubrication. Records of the same model of circuit breaker were also compared to each other, this allowed the prioritisation of which circuit breakers deserved the most immediate attention. Lastly the record would be compared to a record of an overhauled mechanism as this was regarded the best possible reference.

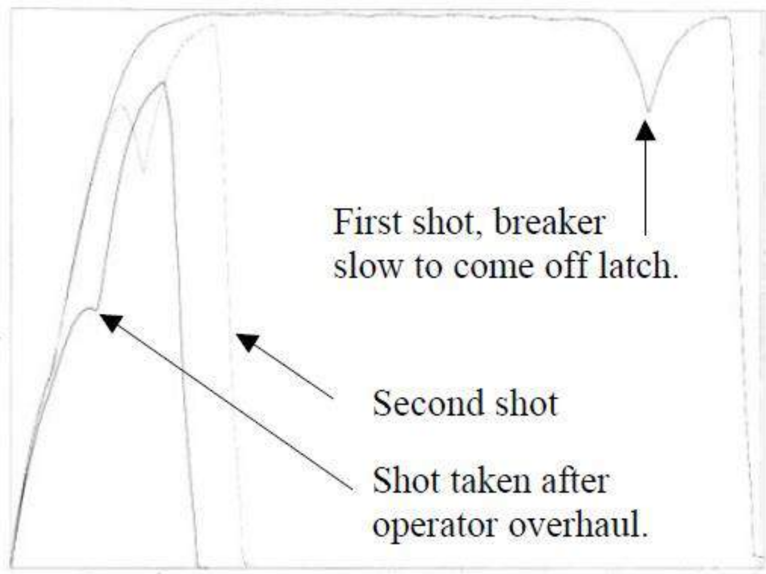


Figure 4-25: Evidence of faulty lubrication

Early in the program they focused on the circuit breakers which showed large noticeable differences in their records. These were identified as circuit breakers in a critical failure mode. As they gained experience they began to realise that slight nuances between two records from the same circuit breaker could be significant and should not be overlooked. In other words, records from a healthy circuit breaker should have identical records not only on their first and second trips, but on their trip records compared over months or years of time.

TXU Electric found that most circuit breakers would show a difference between the first and second trip but this was not true for all types, even if they had lubrication issues. In order to resolve lubrication issues they found that the mechanisms needed to be fully disassembled and lubricated. They also changed the type of lubrication used from petroleum based grease to synthetic.

In summary TXU Electric believes that coil current profiling is an effective tool to not only find defective lubrication issues amongst other issues but also to prioritise circuit breakers that need maintenance and ones that don't.

In [Larson2009], case studies are provided by three North-American utilities. For instance, National Grid has measured coil current of the first three trip operations of an oil CB. Very slow trip operations were noticed (Figure 4-26). After investigating the operating mechanism, it has been found that the trip latch roller was not correctly lubricated.

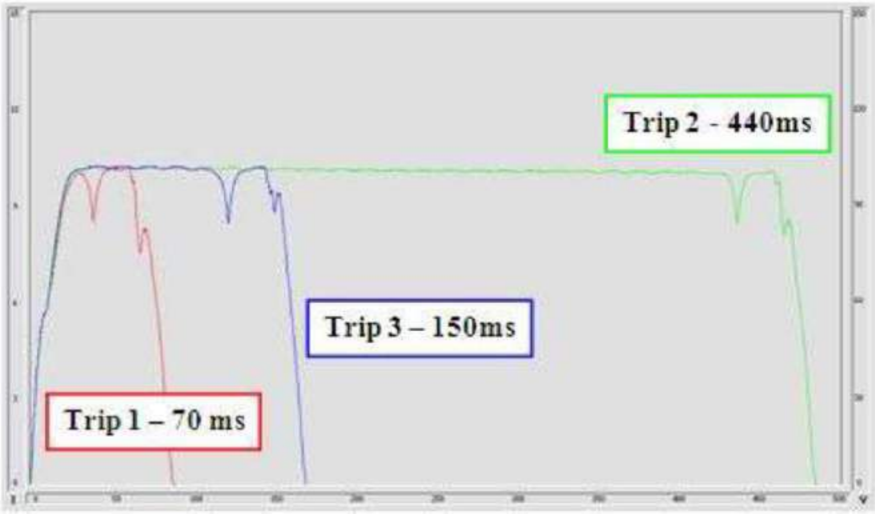


Figure 4-26: Coil current of the first three trip operations of an oil CB [Larson2009]

Figure 4-27: Lacking of lubrication of a trip-latch bearing (left-hand side) [Larson2009]

4.3.8 Experience with Partial Discharge Measurements on MV Switchgear

PD measurements include a family of methods that are generally accepted in the industry as providing good indicators for switchgear insulation deterioration. The condition assessment of electric power equipment by means of partial discharge measurements is widely and intensively documented in the literature. Furthermore, some international standards specify test procedures (ex. IEC 60270) and others provide some acceptance criteria for PD levels (ex. IEC 62271-203). Nevertheless, returns of experience from users are rather seldom reported in the literature. Some users have reported examples of applications where PD was used in continuous monitoring [Boltze2011] and some of its advantages over periodic tests are depicted.

By assuming that the rate of deterioration of an insulation defect may vary a lot, PD periodic can be ineffective in most situations. Periodic readings are sometimes perceived as time- and effort- consuming if they require an expert to take and analyze the data. Also, false negative diagnostic errors during periodic PD tests in switchgear can result in a "false sense of security" [Blokhintsev2009].

A main drawback of continuous PD monitoring is the occurrence of false positive diagnostic errors due to misinterpretations. Many external factors may affect PD measurements and may blur the interpretation of results. First, in outdoor installations, electromagnetic interferences generated from external discharges (corona effect in busbars and connections, radio broadcasting, switchgear operations, etc.) may significantly affect PD readings [Lopez-Roldan2013]. Also, it is recognized that PD activity may fluctuate over long periods of time, as it is depending upon several factors such as system voltage, temperature and humidity. Thus, it is essential to measure those external factors and put PD activity in correlation with ambient fluctuations to distinguish the evolution PD patterns solely due to impending failure of the equipment.

A particular challenge for testing PDs in MV switchgear is to cover a wide area (long switchgear line-ups) with good accuracy [Blokhintsev2009]. Depending on PD sensor sensitivity and noise level, a good location of PDs will be influenced by the number of measurement points by unit length.

The following examples of switchgear failure detected by means of PD measurements have been found in the literature:

- Irregularities at Circuit Breakers (Voltage Grading in Epoxy Resin of Vacuum Tube) [Boltze2011]
- Fiberglass supports' tracking in 34.5 kV switchgear [Blokhintsev2009]
- Damaged bus in several sections of a metalclad switchgear [Garnett2011]
- Strong presence of dust, oxydation and evidence of arcing on a metalclad circuit breaker [Garnett2011]

Different "drivers" may lead users to invest in PD testing solutions. Some of them are explained in [Renforth2011]: Health & Safety, to support reliable life extension projects and to avoid unplanned outages and downtime.

4.3.9 Experience with Dynamic Contact Resistance Measurement

Case studies found in the literature reveal that the DCRM is mostly applied on high-voltage SF_6 CBs, although it can also be applied on MV SF_6 CBs. This method has existed for more than 20 years and nowadays, several test equipment suppliers offer a DCRM kit and praise this method as an effective test to assess contact condition without the need to dismantle. So far, DCRM is not considered as a usual, well established method, since no international standard or guide is available for specifying requirements and recommended practices. Also, only a few utilities has integrated this method as a usual testing tool in its maintenances practices. As an example, the Powergrid Company in India introduced the DCRM method in 1998-99 for 220 and 400 kV circuit breakers [Sodha2012]. Among a circuit breaker fleet of 2700 CBs, about 80 defective circuit breakers have been identified with the DCRM method. The Powergrid Company now utilizes DCRM as a regular decision-making tool regarding inspection and overhaul. In other utility companies, like Hydro-Québec, DCRM is rather used occasionally during investigations, for instance when defects are suspected in the interrupting chambers. Other users have been discouraged from using this method because of the difficulties and ambiguities arising from results interpretations [Landry2004].

The main attraction of the method is its ability to detect abnormalities inside interrupting chambers. It is also recognized that some defects, like excessive erosion of arcing contacts, could not be detected with more conventional tests, such as timing tests and static contact resistance tests. If the DCRM does not show any abnormality, an unjustified internal inspection would be avoided. Internal inspection of SF_6 interruption chambers proved to be a long and complex task which, in most cases, allowed only to confirm the good condition of the internal parts of the interrupting chamber. Internal inspection of a SF_6 interrupting chamber comes with several drawbacks, such as:

- Long duration and high cost
- Tedious handling of SF_6, gas mixtures and their by-products
- Need for specialized tools that are not always available
- Need for specialized parts (O-rings, greases, etc.)
- Probability of lowering the reliability of the circuit breaker after the intervention (ex. wrong assembly)

Usually CB manufacturers recommend major overhauls, including internal inspections after about ten years of service or depending on the number of switching operations. In the past, a decision to proceed with internal inspection of an air-blast circuit-breaker was rather easy to take because no complex gas handling was required. Based on PowerGrid experience [Sodha2012, Bhole2015], some failures occurred within interrupting chambers which have not completed ten years of service and conversely, some CBs opened for inspection after 17-20 years of service had no abnormalities.

Based on the experience reported in [Landry2008, Lalonde2012, Sodha2012], potential types of defects that can be detected with DCRM include:

- Contact misalignment (off-center moving parts);
- excessive erosion of main and arcing contacts;
- loose parts (screw, coupling bolts, etc.).

Like the vibration analysis, DCRM analysis relies on the comparison of a measured resistance curve with a reference curve, which can be, for example, a fingerprint obtained during a commissioning test. The diagnostic is somehow based on the deviation between both curves with a quantitative or qualitative analysis. An example of quantitative analysis is given in [Landry2004] with reference parameters of the main and arcing contacts as well as main and arcing contacts penetration distances. In [Lalonde2012], in the absence of a reference DCRM signature, it was easily found that a potential defect was present in phase A just by comparing three phases (see Figure 3-12). After dismantling the CB interrupter, a poor silver-copper contact was found. As is mentioned in Sodha2012, experience showed that "any minor defect in a CB gets amplified in the signature and makes the analysis simple even if earlier signatures are not available".

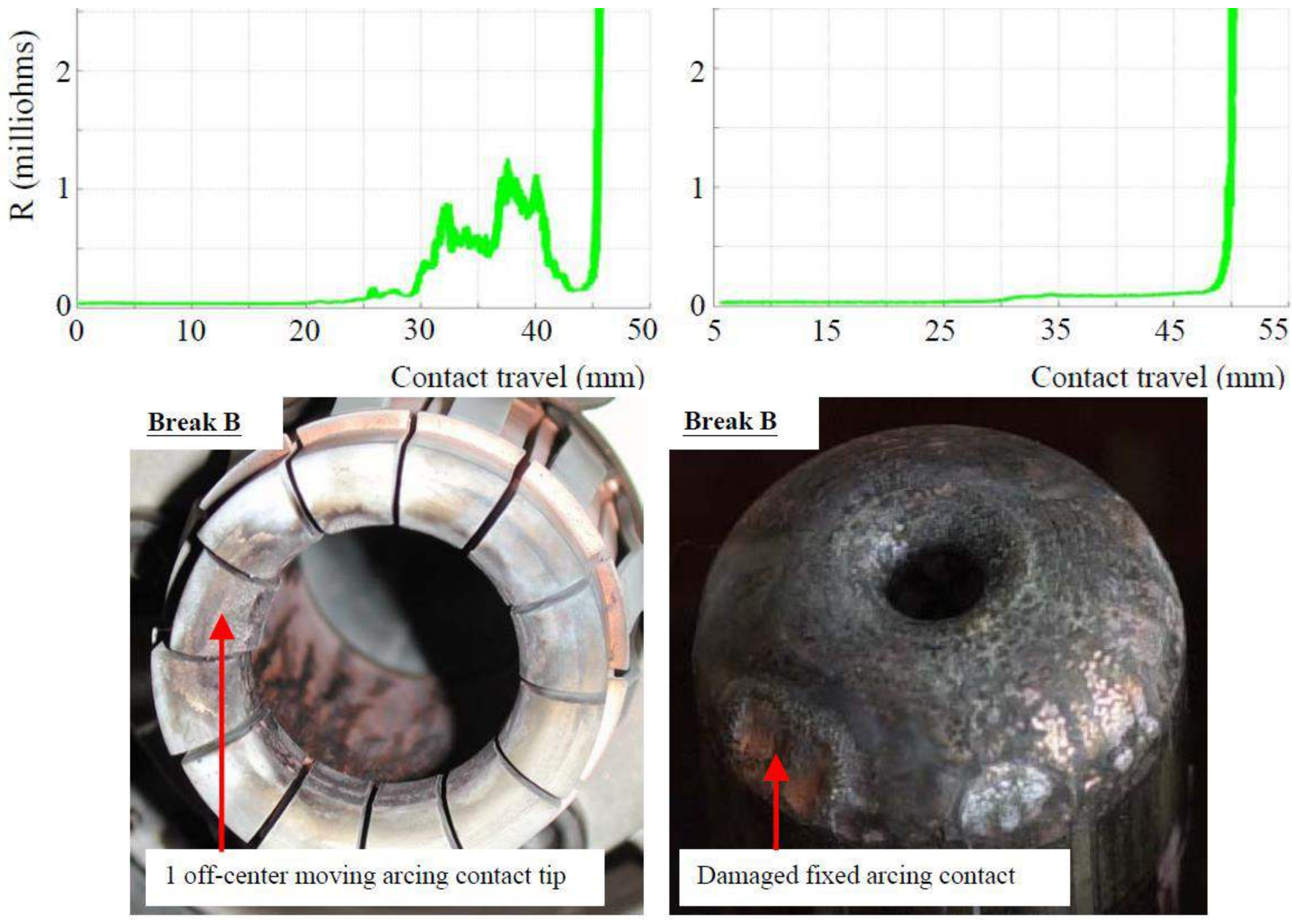


Figure 4-28: Examples of defects detected thanks to the DCRM method [Landry2004]

The measurement of a high contact resistance should not be automatically associated to be a bad condition of the main or arcing contacts. In some situations, false positive errors may arise from measurements taken on some particular designs of CB. For example, in [Landry2008], it is explained that for some MV "sealed-for-life" SF_6 CBs, a resistance measurement performed across the CB terminals does not allow to the direct reading of contact resistance since other parts in the measurement path may increase the overall resistance. Consequently, the actual main contact resistance may be hidden by a high-resistance component in series with the main contacts. In the investigation conducted in [Landry2008], abnormal high-resistance measurements have been attributed to roller contacts that were covered with a thin layer of fluorides and sulfurs (arc by-products), which do not indicate a bad condition of the CB or a decreasing of its performance (ex. breaking capacity). For reducing the measured resistance and being able to discriminate the contact resistance from the roller contact resistance, a high current has been injected for several minutes in order to burn the thin layer across roller contacts. Furthermore, if the following resistance measurement is taken too quickly after injecting a high-current for several minutes, the temperature rise of the contacts will tend to increase the measured resistance.

A reliable diagnostic based on resistance measurement could only be guaranteed if the user has a deep knowledge of the CB design under investigation and its design particularities. The user should also be aware of the various parameters that may influence the measured resistance. In the case where a high-resistance is observed, the user should be able to distinguish an actual high resistance due to the main or arcing contacts from high resistance caused by external factors.

4.3.10 Experience with Wireless Temperature Monitoring

Wireless temperature monitoring systems have been successfully retrofitted in multiple existing installations to measure the temperature of the contacts, circuit breakers, and load break switching devices in metal-clad and metal-enclosed MV and HV switchgear. The data from the multiple sensors are transmitted to the receivers which are connected to the data acquisition system. Users are setting various levels of alarms. Procedures were developed on actions to be taken in case of receiving such an alarm.

Most benefits of such installations were achieved when the measured temperature correlated in real time with load data and ambient conditions (ambient temperature, humidity, atmospheric pressure, etc.)

In [Livshitz2004] an example of such a retrofit is given. The wireless temperature monitoring system has been installed inside station service MV switchgear in a power plant in USA (Figure 4-29). The metal-clad switchgear was originally supplied in the late 1960's and suffered from multiple thermal failures over the years. Wireless sensors have been installed on all (6) fingerclusters of the 3,000A MV draw-out circuit breakers (Figure 4-30). Similar sensors were installed inside the circuit breaker compartments to monitor the ambient temperature.

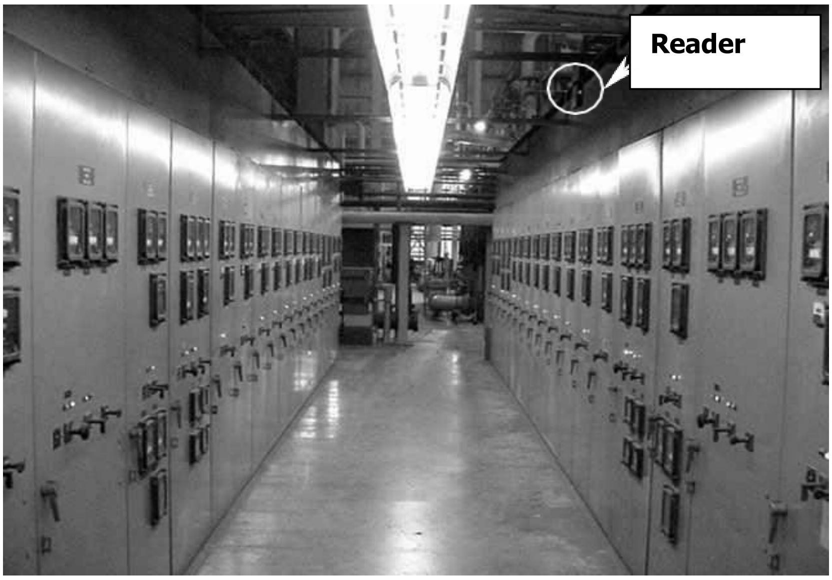


Figure 4-29: MV Switchgear with temperature monitoring system installed at power plant in USA [Livshitz2004]

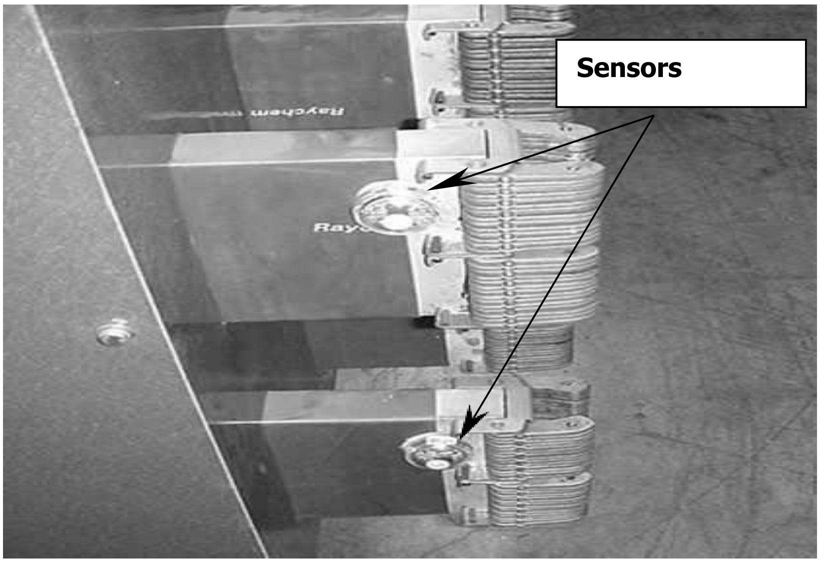


Figure 4-30: Wireless temperature sensors installed on fingerclusters [Livshitz2004]

After only a month of monitoring it was uncovered that the absolute temperature of the fingerclusters on multiple occasions would reach up to 100° C while the load current was about two-thirds of the rated continuous current for these circuit breakers. It was also noted that the ambient temperature inside the breaker compartments would reach 60° C.

The doors of the breaker compartments were modified and forced cooling was installed. After these modifications all temperatures of the circuit breaker fingerclusters and ambient temperatures inside the breaker compartments dropped by 10° C on average. This helped to avert another thermal failure of the circuit breakers. Such failures would be typically associated with prolonged and costly switchgear repairs and service interruption.

4.4 SUMMARY

The actual utilization of non-intrusive diagnostics has been depicted by two means: an international survey conducted by the JWG and a selection of recent case studies found in the literature. As can be seen from the case studies reported in this chapter, non-intrusive diagnostics are often based on indirect measurement of some physical phenomena (ex. radiated UHF signal generated from a partial discharge). Therefore, a lot of effort is required to process and analyzethe measured data. On the other hand, these non-intrusive diagnostic methods are very attractive from the user point-of-view due to their relative simplicity to use and their moderate impact on grid operations. Many examples in this chapter showed how such non-intrusive diagnostics have been successfully applied to various types of switchgear. It allowed, in some cases, to avoid major failures by detecting on time a malfunction or the beginning of degradation and to schedule a maintenance based on the actual condition of the switchgear.

5. TECHNICAL AND ECONOMIC EVALUATION OF NON-INTRUSIVE CONDITION ASSESSMENT METHODS

5.1 INTRODUCTION

One of the most important elements in a power transmission and distribution grid is the circuit breaker. Under normal operating conditions in the closed state, it acts as a perfect conductor carrying the nominal current with minimal losses. In the open position, it acts as a perfect insulator withstanding the nominal network voltage as well as transient overvoltages between its terminals. In the case of a short circuit event, the circuit breaker shall interrupt without producing unacceptable overvoltages or reduce the device's operational integrity.

In order to take informed decisions regarding the residual life of the circuit breaker and its maintenance strategy, proper condition assessment methods are necessary. Excluding defects caused by inappropriate design, assembly, production, erection, and operation; the benefit of assessment methods discussed here refer only to the ageing and wear characteristics of the circuit breaker in service and its resulting reduction in performance and reliability. These also fall under the classification of non-intrusive condition assessment methods (NICAM), which are methods that require only non-intrusive intervention to the switchgear preserving its integrity and allowing its return to the grid without any further verification. Intrusive methods are not considered in this document.

Granted technical maturity, the technical and economic benefits of non-intrusive condition assessment methods must be weighted taking into account its implementation costs, installation, maintenance, operation and data utilization versus the costs generated by the possible failures the equipment might encounter between maintenance periods. While, the implementation costs, can be easily taken as fixed costs and, hence, generalised over the equipment population, the failure resolution costs, on the other hand, involve a more detailed evaluation and assertion of risk. The probability of occurrence of any given failure event and the impact this may have on the surrounding equipment in the substation and ultimately to the network has a more individual characteristic that needs to be taken into account on a case by case basis.

This chapter presents the state of the art methodologies to assess the technical and economic benefits of non-intrusive condition assessment methods. It starts with a collection from the literature of the different failure modes and condition indicators as described in Chapter 3 along the switchgear lifetime. The proper identification of each of the failure modes of the switchgear under evaluation is key to the selection of the condition assessment method. Next, a compendium of the different analysis techniques to evaluate the economic benefits over the technical ones for a given situation is presented. Each of the assessment stages is presented with an example to illustrate the different aspects of a non-intrusive condition assessment method selection and evaluation.

5.2 FAILURE MODES

The importance of understanding the failure characteristics, mechanisms or modes that the network switchgear may encounter during its operational life is linked to the application of condition assessment methods and their associated economic benefits.

The term failure, means the unsuccessful performance of function regardless of cause, component, or device involved. Failure to perform the intended function does not imply that the particular component failed, but that the component or system function was not satisfied. The evolution of how a failure develops over time is known as the failure pattern. Failures can occur very suddenly or over a long period of time and may vary in nature with the types of devices and the physics and chemistry of the failure mechanism.

In [IEEE2000], eleven failure characteristics are described. The failure pattern is to be considered when a condition assessment method is selected as its benefits might differ during different periods of expected failure probability. The understanding of the possible failure characteristics determines whenever the use of a specific monitoring method would be beneficial, for example in the case of a high expected failure probability or if the monitoring method can be avoided completely or change its implementation from continuous to periodic in cases of anticipated lower failure rate.

Similarly, in [CIGRE_462_2011], four evolutionary failure patterns, intermittent, binary, fast wear, and slow wear are discussed. These patterns are another representation of how the physical mechanisms affect asset life.

In reality, there is no unique failure characteristic that can be attributed to the switchgear condition indicators. Approximations need to be done. It is trivial, that the selection of condition assessment methods is simplified if the failure characteristic is understood. It is up to the final user, to identify early enough the failure characteristic and select the best condition assessment method accordingly.

Generally, the failure modes as presented in [IEEE2000] and [CIGRE_462_2011] cover most of the failure characteristics typical of transmission and distribution switchgear. In the particular case, a specific failure characteristic is not available or unknown, a frequency of failure that increases exponentially with age provides good guidance. This is based on the Gompertz-Makeham law of mortality. Different asset groups experience different failure rates and, therefore, different probabilities of failure so the shapes of the failure and probability curves are different [CIGRE_541_2013].

Without overgeneralizing, typical failure mechanisms of T&D switchgear can be attributed to any condition indicator of an asset in the grid. The description presented in Table 5-1 is an example based on the experience of utilities and manufacturers. As mentioned above, it is up to the end user, to assign the suitable failure mode to each condition indicator in each asset in its inventory.

In Figure 5-1, a schematic of a live tank high voltage circuit breaker is shown indicating the location of the condition indicators of the example. Other condition indicators not shown in Figure 5-1 are exclusive of other technologies i.e. gas insulated and dead tank switchgear.

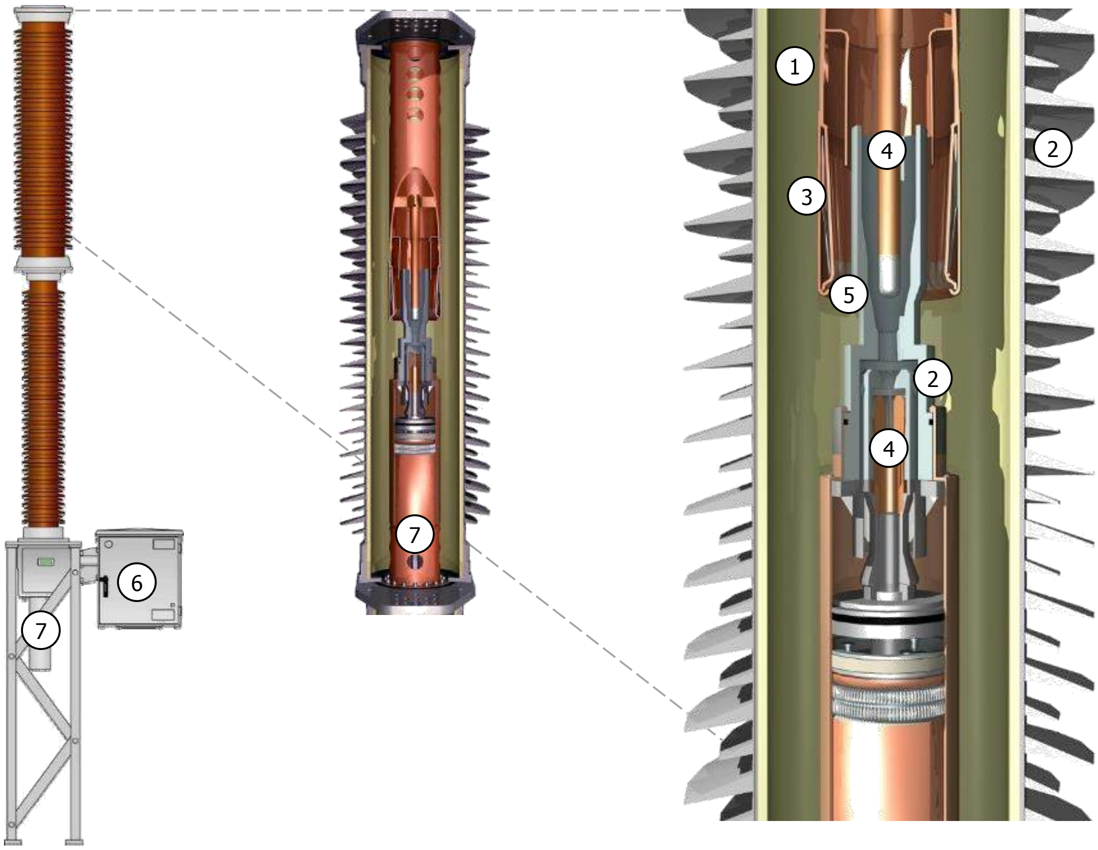


Figure 5-1: Live tank high voltage circuit breaker and failure modes locations

Table 5-1: Example of typical failure mode characteristic attribution to different condition indicators in switchgear

Failure Mode / Location	Description	Typical Characteristic(s) as in [IEEE2000]
Loss of insulating and arc extinguishing medium / 1	Leakage and/or degradation of the insulating medium over the switchgear's lifetime by chemical, physical or thermal processes can cause progressive or immediate dielectric failures across insulated distances in the switchgear. The typical insulating media in current gas insulated equipment is air, SF_6, SF_6/N_2 and SF_6/CF_4. New gases and gas mixtures are expected to behave similarly with respect to leakage and degradation; hence deserving equal consideration as a failure mode. In the specific case of SF_6, this is considered as a very potent greenhouse gas and is included in several climate policy agreements worldwide for a gas to be strictly regulated and in some specific applications to be phased out. The typical parameters to monitor in the case of gaseous media are pressure, density, quality, humidity, and decomposition by-products. This failure mode can affect the operation of the switchgear under both normal and abnormal operating conditions.	Infant mortality followed by a constant or gradually increasing failure rate and then a pronounced wear out region (bathtub curve). Constant or gradually increasing failure rate with time followed by a pronounced wear-out region.
Damage of insulating materials / 2	Surface damage, treeing, cracks and material decomposition can all compromise the circuit breaker's reliability. Electric discharges might be caused by surface pollution, deposition of conductive particles, surface conductivity degradation due to chemical reactions with the insulating medium or material imperfections during manufacturing i.e. microbubbles and voids or asymmetry material mixture composition. The typical parameters to monitor are surface and volumetric quality (voids, tracking, treeing) and partial discharges. This failure mode can affect the operation of the switchgear under both normal and abnormal operating conditions.	Constant or gradually increasing failure rate with time followed by a pronounced wear-out region. Gradually increasing failure rate with no identifiable wear-out region.

Failure Mode / Location	Description	Typical Characteristic(s) as in [IEEE2000]
Damage on main contacts / 3	This type of failure is caused by normal and abnormal operation of the circuit breaker. Damage to the main contacts can compromise the equipment's capability to conduct the nominal current without producing excessive Joule heating. In some cases, the damage can affect the surface resistance of the contacts i.e. commutation marks, thus affecting the commutation process. The typical parameters to monitor are temperature, resistance and burning (commutation) marks. This failure mode can affect the operation of the switchgear under both normal and abnormal operating conditions.	Constant or gradually increasing failure rate with time followed by a pronounced wear-out region. Gradually increasing failure rate with no identifiable wear-out region.
Arcing Contacts Erosion / 4	Typically composed of Cu/W mixtures, the arcing contacts in circuit breakers erode due to arcing. Depending on parameters such as current amplitude, arcing time, total charge, and material properties, the electrical and mechanical erosion defines the geometry of the arcing contacts. Moreover, this geometry determines the performance of the circuit breaker for some or all test duties. If erosion is excessive, it can also affect the commutation process in high voltage circuit breakers. The typical parameters to monitor are erosion, length, the summation of interrupted currents, and travel (position, coordination with respect to main contacts, and acceleration). This failure mode can affect the operation of the switchgear only under abnormal operating conditions; i.e. short circuit interruption.	Gradually increasing failure rate with no identifiable wear-out region.
Nozzle Ablation / 5	In modern circuit breakers, poly-tetra-fluoro-ethylene (PTFE) is typically used as the insulation and gas flow guide material. For circuit breakers of the self-blast type, PTFE is also used to create the necessary pressure for the interruption process. Besides procuring the necessary pressure for current interruption and arc quenching, the ablation of nozzle	Constant or gradually increasing failure rate with time followed by a pronounced wear-out region. Gradually increasing failure rate with no identifiable wear-out region.

Failure Mode / Location	Description	Typical Characteristic(s) as in [IEEE2000]
	material also changes the internal geometry of the nozzles. This, in turn, might influence the partial or total switching performance of the circuit breaker. The typical parameters to monitor are ablation (i.e. changes in geometry), and gas composition by detecting traces of C_2F_4 and CF_4. This failure mode can affect the operation of the switchgear only under abnormal operating conditions; i.e. short circuit interruption.	
Failure of Operating Mechanism / 6	Depending on the type of operating mechanism used (i.e. spring, hydraulic, or pneumatic) and the configuration applied (i.e. TPO or SPO), different failure modes can occur that can affect the operation of the switchgear under normal and abnormal conditions. The number of operations is a determining factor in the health condition of the operating mechanism. The typical parameters to monitor are travel, velocity, acceleration, force, damping, oil level, gas pressure, spring charging time, spring charging energy, operating time, the number of operations, and coil current. This failure mode can affect the operation of the switchgear under both normal and abnormal operating conditions.	Constant or gradually increasing failure rate with time followed by a pronounced wear-out region. Gradually increasing failure rate with no identifiable wear-out region.
Change in the Kinematic Chain / 7	The increase in friction and travel curve characteristics can be threatening to the condition of the switchgear's normal, during, and after operations. This can be caused by pollution i.e. solid particles after a short circuit interruption, degradation of the lubricants by ageing or chemical reactions with the surrounding materials. This failure mode can affect the operation of the switchgear only under abnormal operating conditions; i.e. short circuit interruption.	Gradually increasing failure rate with no identifiable wear-out region.

Once the condition indicator is understood following the guidance of Chapter 3, and the failure mechanism identified as exemplified above, the economic evaluation can start.

5.3 ANALYSIS TECHNIQUES

Several techniques can be used to assess the benefits of utilizing condition assessment methods. Each of these techniques presents its own advantages and shortcomings and the choice is to the end user of which technique or combination of these is more suitable for its assets base management.

From different perspectives, all the methods compare three main cost elements:

1. Investment on the condition assessment system
2. Cost of failure/outage with and without condition assessment (Involves a risk assessment)
3. Cost of maintenance with and without condition assessment (Time Based Maintenance vs Condition Based Maintenance)

An important element is the definition of the End of Life of the asset and the evaluation of benefits of its assertion based on its conditions instead of statistics or age. This distinction allows individual maintenance schedules starting with assets deemed critical and deferring intervention on the ones still in a healthy condition. From a quantitative viewpoint, this means assigning a certain reliability of the condition assessment system applied and an associated failure risk reduction calculation ultimately exposing the benefits of the applied NICAM.

The risk acceptance level for any specific asset is also a factor to consider. Common sense concepts like failure damage, outage time, environmental impact, image consequences and others must be turned into monetary values in order to be used in the evaluation of applying or not a condition assessment method. The criteria used should be homogeneously defined and used for all the assets under evaluation in order to come to a balanced decision strategy.

In 2000, Working Group 13.08, published [a guide to managing the life of circuit breakers. The use of Life Cycle Cost (LCC) analysis is discussed. In this technique, all cost components that occur during a circuit breaker's life are inventoried and their future costs recalculated to present values compensated for inflation. Building on top of the LCC technique, Monte Carlo simulation can be used to reduce the uncertainty level where timing and costs failures, forced outages, planned and corrective maintenance and disposal methods are all represented as probability distributions. The consideration and inclusion of all the costs in any evaluation technique is central. All costs that accrue from purchasing, installation, operation, maintenance (preventative and corrective), adaptations, outages, dismantling, and disposal must be accounted for. Special attention must be paid to the accounting practices of utilities and countries where salvage value and depreciation methods among others could influence the evaluation of economic and technical benefits. Ideally, the GAAP are used to reduce uncertainty in the assets valuation.

That the ultimate goal of condition assessment methods is to reduce costs, these can be justified if the net benefit results are positive from its application. The cost of monitoring should be related to equipment cost and its importance. In the same work, it is noted that although there are no rules for determining the benefits of condition monitoring, certain trends can be observed. For example, for an old switchgear, the costs of installation and application of new monitoring techniques are higher in comparison to a new switchgear. However, it is with the older equipment where new monitoring methods are of the most importance.

In 2001, the IEEE Standards board, introduced a guide for the selection of monitoring for circuit breakers [IEEE2000]. Here the use of Failure Mode and Effects Analysis (FMEA) is selected as the method to determine the possible failure characteristics of a specific family of circuit breakers and this information is used to select the most appropriate monitoring method. Once the monitoring method is selected, a risk assessment is done to quantify the risk associated with each circuit breaker failure mode and a cost-benefit analysis performed to support the final decision of either implementing continuous or periodic monitoring.

In 2004, Working Group A2.20 approached the subject of transformer management from an economic viewpoint [CIGRE_248_2004]. Particularly useful, the repair versus replacement dilemma is approached through normative models and decision charts, where several are presented to aid the decision process.

In 2010, Working Group C1.16 looked into the management of transmission assets and the economic benefit of monitoring [CIGRE_422_2010]. An objective, for operational asset managers and maintenance engineers, is the ability to determine and control the failure risk of a specific asset and its associated maintenance schedule. Based on statistics and expert knowledge, different scenarios can be estimated assuming a service interval. Several examples are given where service cycles are shown for different scenarios with and without monitoring. With the application of condition assessment methods, it should be possible to profit by a reduced failure rate, making maintenance only when and where it is needed. The savings generated should be higher than the investment for the method itself.

In 2011, Working Group B3.12, studied value capturing schemes from on-line substation condition monitoring [CIGRE_462_2011]. Specifically, the economic justification for the use of condition monitoring used different techniques like:

- Cost Benefit Analysis (CBA), where the total expected cost of online monitoring is compared against the expected benefits both expressed in financial terms and adjusted for the time value of money.
- Lost Opportunity Value (LOV), where the relationship between scarcity and choice is discussed and defines the opportunity cost as the cost related to the next-best choice available to someone who has chosen among several mutually exclusive choices. It is generally used in cases where there is not enough data to make an accurate cost-benefit analysis or if only generalisations are required.
- Qualitative and Quantitative Risk Analysis, where risk is treated as a relative measure ranked in categories such as low, medium, high or determined using measurable objective data respectively. The latter is an extension of the qualitative technique that recognises that quantities used to estimate risk are not always constants or deterministic numbers but rather are better described as statistical distributions. In both cases, the risk is monetized on the financial impact of the use or not of monitoring methods.
- Avoided Maintenance technique, which is based on a comparison of the cost of resources needed for the application of condition monitoring systems compared with the cost of resources without condition monitoring. Since condition monitoring may ease maintenance and failure resolution, the need for resources such as labour, spare parts, vehicles, tools, contractor services, clerical support, and so on may be reduced; consequently, their corresponding costs should be reduced in the same proportion.
- Synthesis technique, where the financial investments in monitoring systems for repairable assets such as circuit breakers is analysed against the repair costs and failure impact.
- System Performance, where Key Performance Indicators (KPIs) of utilities are improved by the reduced risk associated with the use of condition monitoring methods. The benefits are categorised as micro benefits (short term), intermediate benefits (tactical) and macro benefits (strategic).

In 2013, in Working Group C1.25, the decision-making process of asset managers using different risk assessment methodologies is approached [CIGRE_541_2013]. Here, an overview is given on quantitative evaluation of risk treatment plans for grid development and sustainment, and how utilities quantify the monetary consequences for events affecting business values that are not directly measured in financial terms. Environmental impact is specially treated and considered in the decision-making process.

Outside standardisation and investigation bodies, other techniques have been explored. For example, in [Davies2015], Condition Based Risk Management (CBRM), a methodology to calculate the risk associated with large numbers of assets by developing calibrated estimates of each assets probability and consequences of failure, is provided. A quantitative probability of failures per year is derived from an asset ‘Health Index’ which combines known information relating to the assets age, design, operating environment, operating duty and physical observations of the condition. Consequences of failure are evaluated at the individual asset level in financial terms. This is achieved by first developing quantified estimates of the average consequences of failure in the dimensions of Network Performance, Safety, Financial, and Environmental impact. These average consequences are then individualised by scaling up or down to reflect individual assets operating context through the application of appropriate criticality factors. The economic aspect of the CBRM method is based on Net Present Value (NPV) estimations and the payback period taken as the time for the value of mitigated risk to be equal to the investment cost of the equipment plus the sum of the annual operating costs.

5.4 EVALUATION PROCESSES OF NICAM

The choice for a non-intrusive condition assessment method is both a technical and an economic matter. There is no simple answer or one-size-fits-all solution when it comes to the correct criteria and usage of NICAM for installed or planned assets. Figure 5-2 and Figure 5-3 offer possible NICAM selection processes from different starting points.

In Figure 5-2, the selection process of NICAM is shown from the perspective of a technical and economic analysis prior to implementation. The first step is to select the assets to be monitored and select the condition indicators to be assessed. It is important to distinguish between the in-operation age and the manufacturing age, which for some assets might be relevant (i.e. VI's). Having the assets inventoried with their respective age and the condition indicators selected, their failure mode characteristic is to be determined using the methods discussed in 5.2. In the case where no specific failure mode can be confidently assigned, a deeper study is needed to derive a dedicated one. Knowing the failure mode for each of the assets, the selection of the proper NICAM can be done using the references presented in Chapter 3. The last stage involves the economic analysis using the most appropriate method from those described in Chapter 5.3. If the user arrives at the conclusion that the economic benefits surpass the investment in NICAM, the decision to apply these is taken, otherwise the decision can be postponed to a later stage where the overall picture might change.

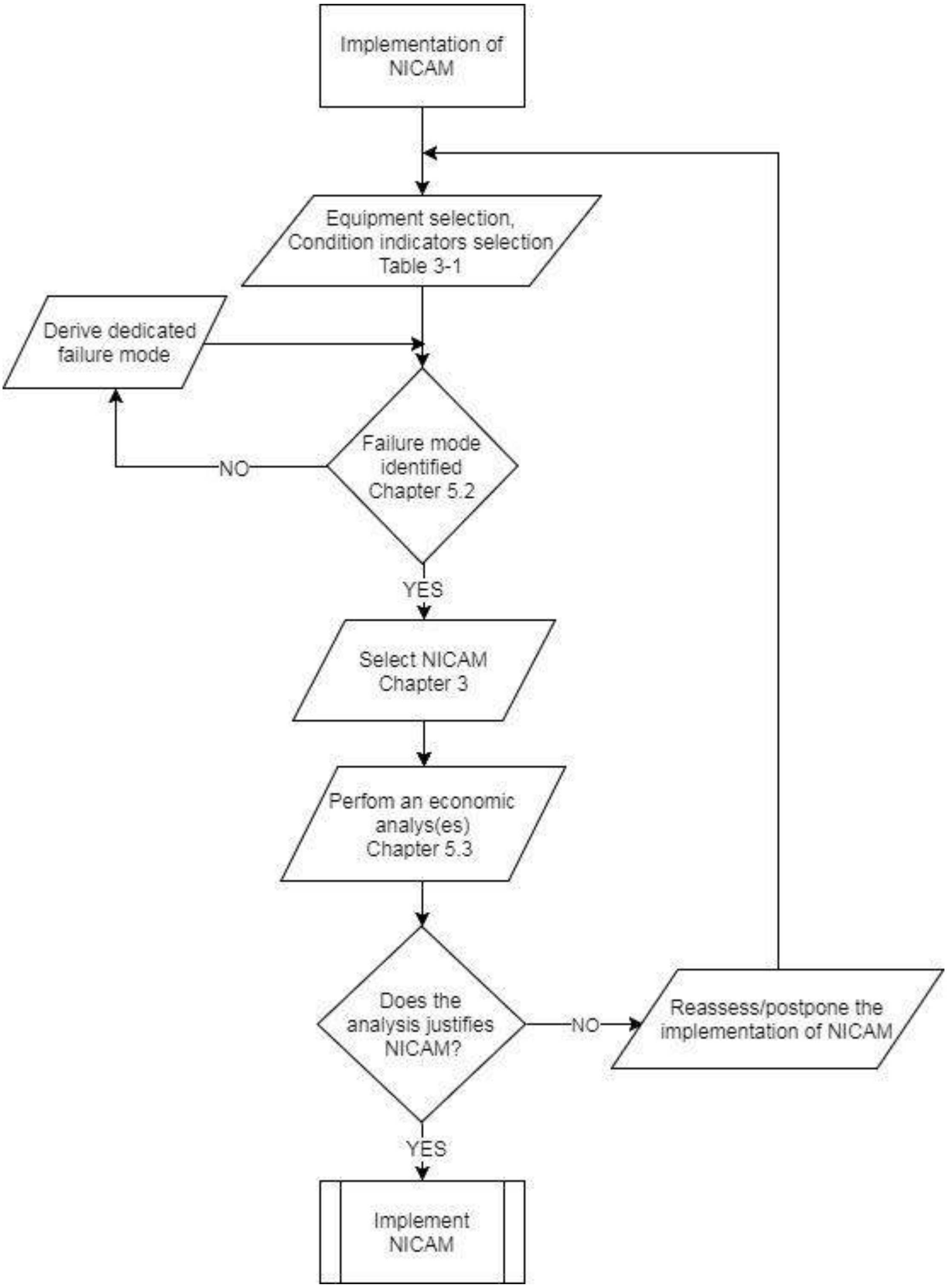


Figure 5-2: Example of a NICAM evaluation process pre-implementation

In Figure 5-3, a different approach is presented. In this case, the user has decided to invest upfront in NICAM and evaluate subsequently the technical and economic benefits of these. If the benefits are substantial, a progressive expansion into further assets is followed. If no benefits from the use of NICAM are identified, the evaluation is repeated at a later stage.

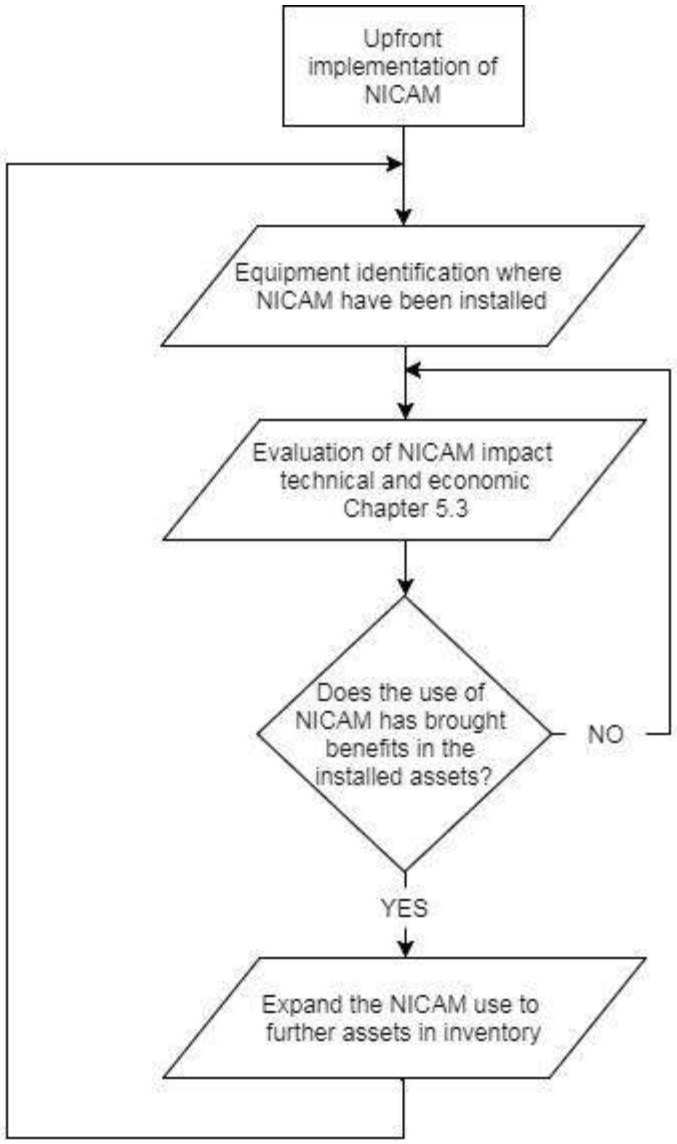


Figure 5-3: Example of a NICAM evaluation process post-implementation

5.5 TECHNICAL VERSUS ECONOMICAL BENEFITS

Several aspects need to be considered when evaluating technical and economic benefits of NICAM. Although the final answer lays on the user side, there are however certain facts and trends that are intrinsic to the question. While the economic benefits of NICAM can vary among users, the technical ones do not. Different trends exist at different voltage levels in the network. For example, at the distribution level, due to the number of assets, the number of operations, short circuits and failures are higher with respect to the transmission level. However, the costs associated with failures are lower in comparison.

5.5.1 Technical Benefits and Usefulness

The technical benefits of NICAM, are strongly related to the type of method and condition indicator to be monitored. The usefulness of each method is strongly linked to the condition indicator to be assessed and the technology used. In the technical evaluation, several aspects need to be considered in order to determine the usefulness of a defined NICAM.

- **Easiness of use** Some methods due to its nature are mature enough and readily available to be implemented in different ways (i.e. temperature), while some might require more elaborate conditions to procure a usable measure (i.e. PD)

- **Easiness of interpretation** While some methods offer a directly measurable variable on the asset (i.e. pressure) some might require data post-processing and interpretation by qualified personnel (i.e. PD)
- **Quality of information** Regardless of the easiness of use and interpretation, different NICAM might provide different levels and degrees and types of information, i.e. a pressure sensor will provide quantitative data on absolute or relative pressure, while gas analysis on top of that will provide gas quality and species.
- **Scalability across all voltage levels and equipment** Some methods might offer a more robust concept to be applied independent of the voltage level, network configuration and type of equipment.

5.5.2 Economic Benefits

The economic benefits of NICAM are visible once several risk factors and their consequences are monetized and interpreted inside the user's framework. It is general to all the works mentioned in 5.3 that the main economic benefits are those related to the costs avoided in the case of failure.

Expressed in similar terms, the economic benefits common to all NICAM are:

- Reduction or total avoidance of outage costs
- Reduction of insurance premiums
- Reduction of repair costs
- Reduction of safety training related costs
- Reduction of costs for studies
- Reduction of maintenance costs
- Reduction of CAPEX
- Reduction of exploratory non-destructive testing
- Reduction of replacement costs
- Reduction of environmental costs
- Reputation costs
- Reduction of driving risk
- Reduction of injury/fatality costs
- etc.

5.5.3 Example of Economic Benefit Calculation of NICAM

In [CIGRE_167_2000] three approaches are given to evaluate the economic benefit of condition assessment systems, going from the microscopic level (analytical approach), middle level (synthesis approach) to macroscopic level (resources driven approach). Here, a simple way of how to evaluate the economic benefit of NICAM is given based on the more general "resources driven approach".

Independent from the specific diagnostic technique or technology, the basic concept is applying methods to assess the switchgear condition along the time, reduction of costs connected to maintenance and operation or to major failure probability of the asset, namely:

- Reduction of outage cost
- Reduction of repair cost

The cumulated economic benefit along the observation time (i.e. from installation of the monitoring system or start of a systematic diagnostic program, to the end of life of the asset) actualized to year zero should justify the investment. Additionally, the lower failure risk resulting from applying NICAM can defer renewal or refurbish of the asset ensuring the same reliability.

As shown in [CIGRE_422_2010], the concept is:

- Risk identification
  - Risk probability
  - Costs connected to the failure event
- Risk = consequence costs * probability of occurence
- Cost of mitigation actions (condition assessment programs)
- Risk acceptance is defined by break-even between value at risk and cost of mitigation actions

Following the same concept, the following can be obtained:

- Failure probability as a function of age
- Cost of failure
- Investment into NICAM able to reduce the failure rate

The use of NICAM can reduce the failure risk probability with a different effectiveness based on the measured condition indicator. Furthermore, the usefulness as described in Chapter 5.5.1, determines the final risk reduction of any specific method applied. The economic benefit is then related to the lower probability of major failures and their associated costs. Taking the use of a NICAM for example,

$$E_i = \sum C_f \times (p_f - p_{f\_NICAM})$$

Equation 5-1

Where:

- C_f : cost of failure
- p_f : probability of failure without NICAM
- p_{f_NICAM} : probability of failure with NICAM

The probability of failure with NICAM will be lower according to Equation 5-2

$$p_{f\_NICAM} = p_f \times (1-U)$$

Equation 5-2

The economic benefit at year i is then,

$$E_i = \sum C_f \times [p_f - p_f(1-U)] = \sum p_f \times U$$

Equation 5-3

The usefulness U of a monitoring system is quantified here as the effectiveness of how a failure can be prevented reducing the associated failure probability. The estimation of the usefulness U is a deciding factor and depends from the typology of monitoring, experience, present detection applied technology, specific asset monitored among others. The use of NICAM should allow a reduction of the failure rate by detecting the possible failure evolution allowing focused maintenance on the asset. This is more effective the higher the usefulness of the NICAM selected. Generally speaking, the following assumptions are valid:

- The failure probability increases with the asset age.
- Without any other parameters available, the dispersion of this information increases as well since the condition of the asset is unknown.
- Monitoring, depending on its usefulness, allows a better assessment of an asset preventing major failure and, by that, reducing the probability of major failures.
- When the failure risk probability decreases the risk value is reduced.

A graphical representation is given in Figure 5-4 where the grey points represent the failure risk probability distribution and the blue and red lines are the 90th and 10th percentile respectively. It follows that:

1) Based on major failure frequency, a line interpolating a probability of failure can be assumed. The failure statistic should be taken from collected data on the specific asset. In case no values are available, existing work on the matter might offer guidance. In this example, [CIGRE_510_2012] is taken as a reference. The better the asset assessment, the higher the asset information available is and the more precise the assumed risk probability curve will be.

2) The asset manager should define an acceptable failure risk probability (red dashed line).

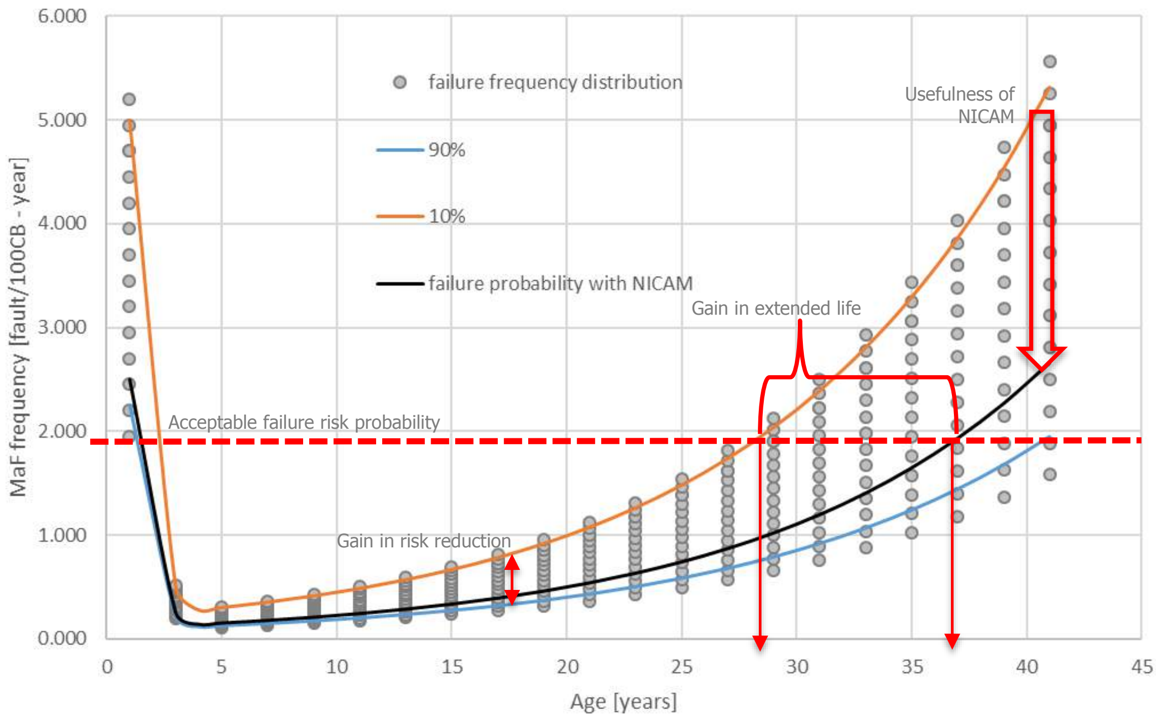


Figure 5-4: Principle representation of frequency of major failure and risk probability curves as a function of the age of asset.

3) If the failure risk probability is reached, refurbishment or renewal is needed. In the example, it is assumed a probability of 2 major failures per 100 circuit breaker per year (red dashed line).

4) Without any monitoring, an upper line of the available statistic should be used in order to cover the majority of the possible cases (for example 90th percentile). In the example, this would lead to a critical age of about 28 years

5) Applying NICAM a lower failure risk probability can be used. The higher the usefulness of the NICAM, the lower the line will be. In Figure 5-4, the application of NICAM would allow using the black line instead of the 90th percentile line.

6) In economic terms, at the current year (i) the saving is proportional to the reduced failure Risk probability multiplied by the cost in the case of failure (Equation 5-1). To determine the total economic benefit along the whole asset life of (n) years, the benefit of every year (i) has to be taken into account with Equation 5-3 once the update rate (r) has been defined. This updated rate considers that the value of money today will be not the same in the future.

$$E_{Cum} = \sum_{i=1}^{n} \frac{E_i}{(1+r)^i}$$

Equation 5-3

7) The investment for the monitoring system should be lower than the cumulated saving achieved.

8) The benefit could also be seen as extended life before reaching the limit. This would allow an extension of the asset life before reaching the defined failure risk probability limit. From a economical viewpoint, this means deferring replacement or refurbishment.

BENEFIT DUE TO THE REDUCTION OF VALUE AT RISK.

The given values here for risk probability are given as an example, whereas in practice, the asset manager should assign the values taken from specific asset assessment and monitoring. The same is valid for the cost of major failure. It is important to stress, that the outage costs can vary depending on the grid the switchgear is installed on. The same switchgear installed on different grids might cause different outage costs depending on the importance of the grid and the ensured energy delivery reliability.

Table 5-2: Numerical calculation of the economic benefit at year *i*

		Numerical example
Failure Probability w/o NICAM (*n*)	p_f	0.47%
Monitoring usefulness	U	55%
Failure Probability fwith NICAM	$p_{f\_NICAM} = p_f \times (1-U)$	0.21%
Cost of major failure - Asset renewal (100) - Outage (1000) - Additional costs (100)	C	1200
Risk value no NICAM	$C \times p_f$	5.46
Risk value with NICAM	$C \times p_{f\_NICAM}$	3.1
Economic benefit due to NICAM at *i* year	$E_i = C \times (p_f - p_{f\_NICAM}) = C \times p_f \times U$	2.36

Repeating the process for every year starting from the year when the NICAM is applied ($i=0$) until the end of observation time (n) (i.e. asset life), the cumulated actualized economic benefit can be evaluated using the Equation 5-3.

In Table 5-3 the calculation for an observation time of 15 years and an update rate for actualization of 4% is given. The economic benefit of every year is given for example purposes.

Table 5-3 Numerical calculation of the economic benefit for a 15 years time horizon

Year	Economical benefit (values given for the example)	Updating rate	Actualized economical benefit	Numerical example
n	E_i	r	$\frac{E_i}{(1+r)^i}$	
0	2.36	4%	2.36/(1.04)^0	2.36
1	4	4%	4/(1.04)^1	3.85
2	4.5	4%	4.5/(1.04)^2	4.16
3	5	4%	5/(1.04)^3	4.44
4	5	4%	5/(1.04)^4	4.27
5	6	4%	6/(1.04)^5	4.93
6	6	4%	6/(1.04)^6	4.74
7	6.5	4%	6.5/(1.04)^7	4.94

Year	Economical benefit (values given for the example)	Updating rate	Actualized economical benefit	Numerical example
8	6.5	4%	6.5/(1.04)^8	4.75
9	7	4%	7/(1.04)^9	4.92
10	7	4%	7/(1.04)^10	4.73
11	7.5	4%	7.5/(1.04)^11	4.87
12	7.5	4%	7.5/(1.04)^12	4.68
13	8	4%	8/(1.04)^13	4.80
14	8	4%	8/(1.04)^14	4.62
15	8.5	4%	8.5/(1.04)^15	4.72
			$\sum_{i=1}^{n} \frac{E_i}{(1+r)^i}$	71.8

The calculation shows an economic benefit in case of NICAM application for 15 years of 71.8 actualized to the year 0. The investment for the NICAM system is then supposed to be less than this number in order to opt for.

BENEFIT RESULTING FROM EXTENDED END OF LIFE.

Defining an acceptable risk probability implies defining a life span after which renewal or refurbishment is needed in order to be able to guarantee the asset reliability. Figure 5-4 shows the principle representation of frequency of major failure and risk probability curves as a function of the age of asset are shown. It is assumed a failure risk Probability of 2%, without NICAM is acceptable where renewal or refurbishment needs to be planned after approximately 28 years.

Applying NICAM, the failure risk probability (red dashed line) leads to an end of life between 36 and 37 years. A renewal or refurbish deferral of 8 years could be considered without reducing the asset reliability. The economic benefit can then be calculated using again an adapted Equation 5-4 as:

$$Benefit = Asset\ value\left(1 - \frac{1}{(1+r)^n}\right)$$

Equation 5-4

which in numerical terms is:

Renewal costs - Asset value 100 - Installation costs 20	120
Update rate	4%
Renewal deferral	8 years
Updated asset value	87.7
Benefit	32.3

The calculation shows that assuming renewal costs of 120, the economic benefit of the renewal deferral can be estimated in 32.3. It must be noted that the values are on purpose without currency and given for exemplification purposes.

5.6 DIFFERENCES IN THE APPLICATION OF NICAM FOR HIGH VOLTAGE AND MEDIUM VOLTAGE ASSETS

Non-intrusive condition assessment methods have different degrees of impact depending where in the network they are used. A summary of the differences of the use of NICAM in HV and MV assets is presented.

Table 5-4: Differences of NICAM usage in HV and MV assets

	High Voltage	Medium Voltage
Main Motivation	- Avoid unplanned outage - Extend the asset lifetime	- Avoid unplanned outage
Investment in NICAM Costs	- Low in comparison with the asset price. - Low as per the number of assets to be serviced	- High in comparison with the asset price. (As a rule of thumb, it should not exceed 10% the asset price) - High as per the number of assets to be serviced
Functional impact	- High for transmission assets	- Medium to high in primary distribution - Medium to low in secondary distribution
Trend	- Increase usage especially for critical assets in low redundancy topologies.	- Increase usage, especially for primary distribution (oil and gas, hospitals, paper production, etc.)

5.7 SUMMARY

The decision of using non-intrusive condition assessment methods for new and installed T&D switchgear is a question that needs to be answered on a case to case basis.

The technical benefits are incontestable due to the non-intrusiveness characteristic of the methods that do not jeopardise the asset function nor the grid operation. Installation and/or use of these on switchgear before or after testing is a relatively straightforward procedure depending on the method used. The closer knowledge the user has about the condition indicators to be assessed and their typical failure modes, the easier the selection of the NICAM and evaluation. Several failure modes are presented in Chapter 5.2. These cover most of the ageing characteristics of the condition indicators as presented in Chapter 3. Whenever no failure mode can be assigned confidently to a particular condition indicator, a statistical approach is recommended.

Usefulness, an intrinsic characteristic of each method, is a key factor and the major link between the technical benefits of a method and its economic viability. Ease of use, interpretation, quality of information and scalability are the main components whenever usefulness is determined.

The economic benefits are a matter treated differently. Three main cost elements have been identified: investment in the NICAM, maintenance costs with and without NICAM and failure/outage costs with and without NICAM. At the transmission level, NICAM investment costs are usually less of a topic than on the distribution level where these are one of the main drivers. Maintenance costs, share an equal part and importance independent from the voltage level. Failure and/or outage costs are, however, not only the less straightforward to quantify but also the most impacting ones. In 5.5.2 a list of the avoidance costs is presented. Whereas some of these are tangible costs, some others require intangible valuation techniques to monetize and signify their impact.

When evaluating the use of NICAM, there are no identical situations that lead to the same outcome in an economic analysis. Differences in accounting rules, expenditures schemes, risk appetite and others, differentiate users vastly leading to possibly opposite decisions for similar situations. Even for a single user, the choice for the implementation of NICAM could have different perspectives at different points in time. This renders the economic benefits analysis of NICAM a privy and timed matter that should be done as precise as possible, revised and updated regularly.

It is finally to the end user to consciously evaluate the economic benefits that the use of NICAM could bring to its operation. If costs are not a matter of concern, it is always recommended to increase the level of information of the installed base by means of NICAM. Future trends signal a movement of the industry towards a more unified and informed network, which is a topic presented in the next chapter.

6. FUTURE TRENDS

6.1 SWITCHGEAR USER TRENDS

The industry environment has changed radically in the last years. There used to be a large powerful workforce and a depth of knowledge with limited computer power. Now there are large powerful computers and a small workforce with a limited depth of knowledge. This results in new trends in managing and operating the diagnostics and condition monitoring of switchgear. Many utilities do not have switchgear experts which are able to decide what parameters to monitor, develop technology and interprete results. They are replaced by "generalist" engineers who have to deal with other equipment also. Therefore, the know-how is shifted to the switchgear manufacturers and to manufacturers of condition monitoring equipment.

There is also a stricter criteria on safety and low tolerance towards explosive failures in the switchyard. These types of failures trigger the adoption of condition monitoring by the user.

Due to this environment the switchgear user prefer:

- To have expert systems manage monitoring outputs and advice action
- Outsource to specialised companies and manufacturers the management of the condition monitoring of its own plant

6.2 TRENDS IN DATA COLLECTION AND INFORMATION PROCESS

Today it is possible to gather much information on the condition of the switchgear. This data can be gathered continuously and can be centralized [CIGRE_567_2014]. There is a need for expert systems to process this amount of data in a simplified way. The future of continuous monitoring methods depends on having a simple process with clear and defined outcomes, to be implemented by the end user.
The trend to go from periodic monitoring to continuous monitoring will increase the amount of data to analyse and store. There is a need for the integration and interpretation of a large amount of data. This data can be stored in cloud applications. For the data analysis, interpretation and trending, there will be an intensive use of expert systems and artificial intelligence.

6.3 INTEGRATION OF MONITORING INTO CONTROL UNITS

There is a trend to integrate condition monitoring in the control and automation of the switchgear.

In High Voltage applications, there already exists integrated monitoring platforms where all the monitoring parameters are measured by sensors and information is centralized.

In order to apply these monitoring platforms into MV switchgear, the cost of the units should decrease considerably. With the cost of sensors going down, cost of communication going down, with data processing power going up, the trend of increasing the monitoring in MV in the future is expected. This applies to new equipment, but not necessary to the old. However, the installation cost of the monitoring system on the old equpment is not going down.

6.4 INTRUSIVE AND NON-INTRUSIVE MONITORING

The trend for new equipment is to be fitted with sensors where it is possible to gather information on the state of the device. However, there is great need to monitor old plants with the aim to extend the life of installed equipment. There is a preference for non-intrusive monitoring for this application.

One of the issues for extensive application of monitoring in HV switchgear is the shorter life of the sensors and monitoring platforms (10-15 years) versus the life of the switchgear (40 years).

Since HV switchgear is getting smaller, it is more challenging to apply non-intrusive diagnostic methods (dynamic resistance for instance), or find a better example of non-intrusive monitoring.

6.5 APPLICATION OF NON-INTRUSIVE SENSORS FOR MONITORING OF CIRCUIT BREAKER PARAMETERS

There is a clear advantage to use non-intrusive sensors which can be placed outside the live-parts of the circuit breaker. Examples of this type of sensors are:

- Switching diagnostics through electro-magnetic emissions of the arc detected by antennas
- Antennas for detection of partial discharges placed outside the CB
- Transient voltage measurements through capacitive sensors

6.6 MONITORING OF NEW GASES USED IN HV AND MV SWITCHGEAR

Today vacuum and SF_6 are the two main media used in circuit breakers. However, due to the environmental impact of the gas SF_6, there are new alternative gases starting to be used (CO_2, dry-air, N_2…). There will then be a shift from a single gas (SF_6) to different gases depending on the equipment rating and manufacturer.

SF_6 was very well known and standards existed. It is required to investigate long-term evolution of combination of new solid-gas materials in the presence of humidity, oxidation, gas decomposition etc.

6.7 EXPANSION OF THE APPLICATION OF PARTIAL DISCHARGE DIAGNOSTICS

Traditionally PD diagnostics were only applied to strategic and expensive equipment such as EHV GIS substations and cables. The use of PD diagnostics has been extended to MV distribution switchgear.

The trend is to apply PD monitoring not just to GIS substations but also to AIS substations.

Partial discharge interpretation and decision making based on PD diagnostics is still complex and experienced engineers are required for the interpretation. The trend is to implement better expert systems which process the PD data and provide clear and simple solutions.

6.8 MAKING SWITCHGEAR DESIGN MORE SAFE

The increase in safety requirements puts a strong demand in the capability of the switchgear to withstand an internal arc during a fault without risk to the operation personnel. This arc withstand capability is proved by test. There is also an interest to avoid or to reduce the consequences of the internal arc. The application of thermal monitoring and partial discharge diagnostics will reduce the chances of the internal arc by giving early warning. The use of fast operating arc quenching devices triggered by light, sound or current sensors will limit the damage produced by the internal fault.

6.9 ASSET MANAGEMENT

An important outcome of the application of condition monitoring is the ability to use data to predict the end of life of the switchgear. This is a valuable output for the asset manager. The prediction of the end of life allows utilities to make decisions on which switchgear must be replaced and when.

6.10 AUGMENTED REALITY

Augmented Reality (AR) is a technology that superimposes digital information and media, such as 3D models and videos, upon the real world through smartphone, tablet, PC, or connected glasses. One potential use for AR is for equipment maintenance and condition assessment. With AR, technicians in the field can overlay a 3D model on an actual piece of equipment. They also can view the internal components of a piece of equipment, including measurements from sensors and gauges. In addition, AR can also improve operation safety because it allows for better visualization and understanding of the complex assets, thus reducing accidents.

6.11 FUTURE TRENDS IN SENSORS

The macro trend of IoT is leading the drive to more and more sensing options at lower cost, lower power, and increased connectivity. The technology advancements are occurring on three main fronts: sensing element, wireless communication, and battery technology. MEMS (Microelectromechanical Systems) leverage new microfabrication techniques to create sensing elements at the micro scale which can be combined onto a single piece of silicon with other integrated circuits. Temperature, pressure, vibration and strain gauges are a few of the sensing types which are currently available in a MEMS package. Wireless communication protocols such as LoRa, SigFox, BLE, and LTE-M are focusing on addressing the needs of IoT applications. While each of the protocols has different features (mesh networking, range, data bandwidth), they all are becoming lower cost and lower power. Driven by demands of the consumer electronic device market, batteries are becoming smaller with higher energy density. Batteries are also being manufactured in a much wider variety of form factors allowing companies to have more flexibility in the size and form factor of their product to fit specific application needs. In the future, we will see more sensors leveraging the advances in these three areas to create lower cost wireless sensors with longer battery life.

6.12 MONITORING IN CONTROLLED SWITCHING DEVICES

6.12.1 Introduction

The development and modernization of electrical grids, the need for more availability and reliability, the gradual introduction of grid codes and the availability of advanced flexible controlled switching device (CSD) have recently been accompanied by the increase of controlled switching applications.

In order to maintain switching performance, circuit breaker monitoring functions need to be implemented in CSD. The aim is to accurately anticipate circuit breaker operation times (break/make).

The following typical values may be found in CSD:

- Mechanical time, measured from auxilliary sensor
- Circuit breaker voltages and currents (6U/3I)
- Circuit breaker ambient temperature
- Auxiliary voltages

The duties of CSD are:

- For opening operation: to precisely predict the arcing time for each operation by syncing the arcing contacts separation with the circuit breaker current. Every circuit breaker (self blast or puffer) has an arcing time window for which the limits should be avoided. Possible detrimental issues are restrikes and reignitions. Reignitions, which lead to abnormally long arcing times, can be detected with primary current acquisition.
- For closing operation: to determine the making time durations in each pole (which shall anticipate both mechanical time and prestrike time), depending of the load type (transformer, overhead line, capacitor bank…) and voltage conditions at the time of operation. This is in order to reduce detrimentals issues (overvoltages, inrush currents, network voltage sag, harmonics).

6.12.2 Mechanical Time Monitoring (contact touch, contact separation)

Regarding the mechanical aspect, an essential distinction between random scatter and long term drift has to be made:

Random scatter, from one operation to another is something that cannot be compensated. There is no other choice than keeping it low, by design (drive and circuit breaker).

Long term drift is the main reason for a CSD to monitor the mechanical operation times: if the mechanical time measurement sensor (auxiliary contact, travel curve, or whatever solution) is proven to be consistent with the main contact, the drift can easily be compensated by servoing control law. The aim is to compensate for ageing or a running issue. As the required making time accuracy to maintain highest performance is on the order of ±1ms, this compensation is essential.

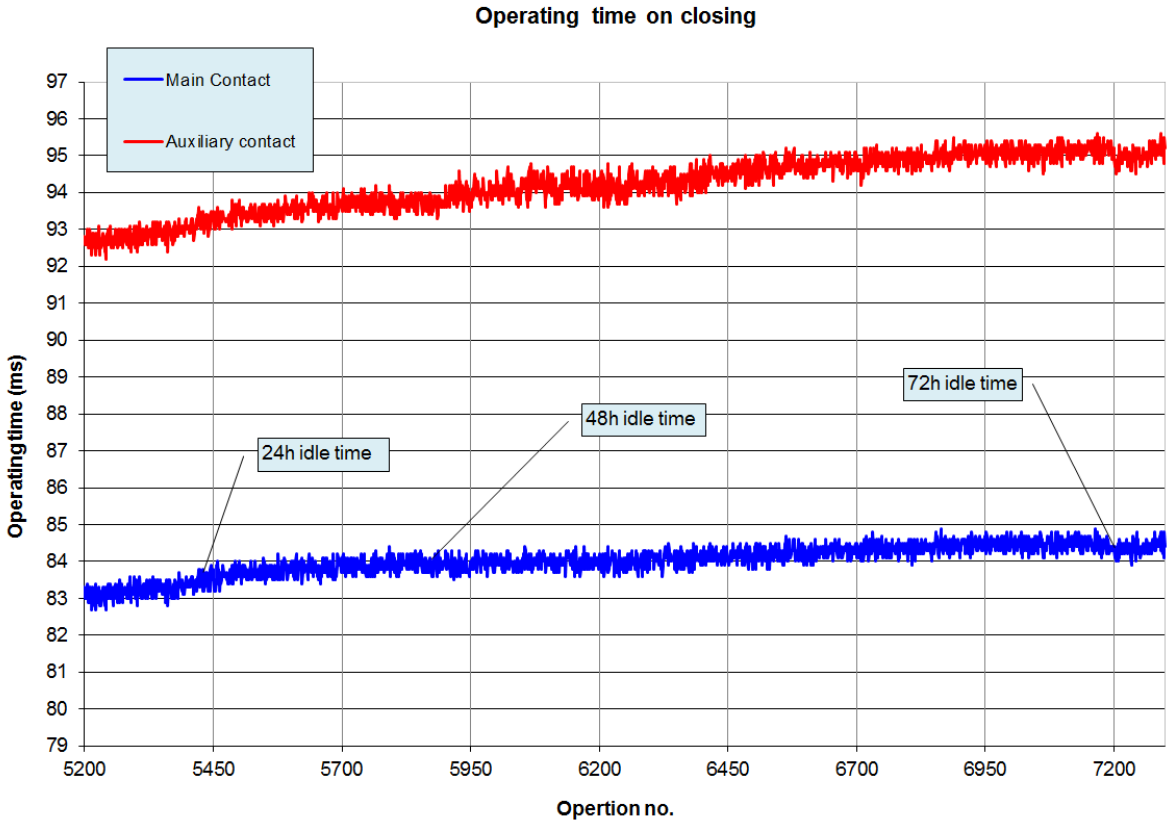


Figure 6-1: Main and auxiliary contact drifts recorded during 10k operation endurance test

6.12.3 Dielectric strength considerations

While overseeing successive closing operations (computing trends, to get rid of random aspects), if performance degradation is observed (wrong making time) while mechanical time seems consistant (or deviation properly compensated by CSD), dielectric strength degradation may be at play.

As likely root causes may be different (contact wear, insulation media) this can only be considered as a general denotation.

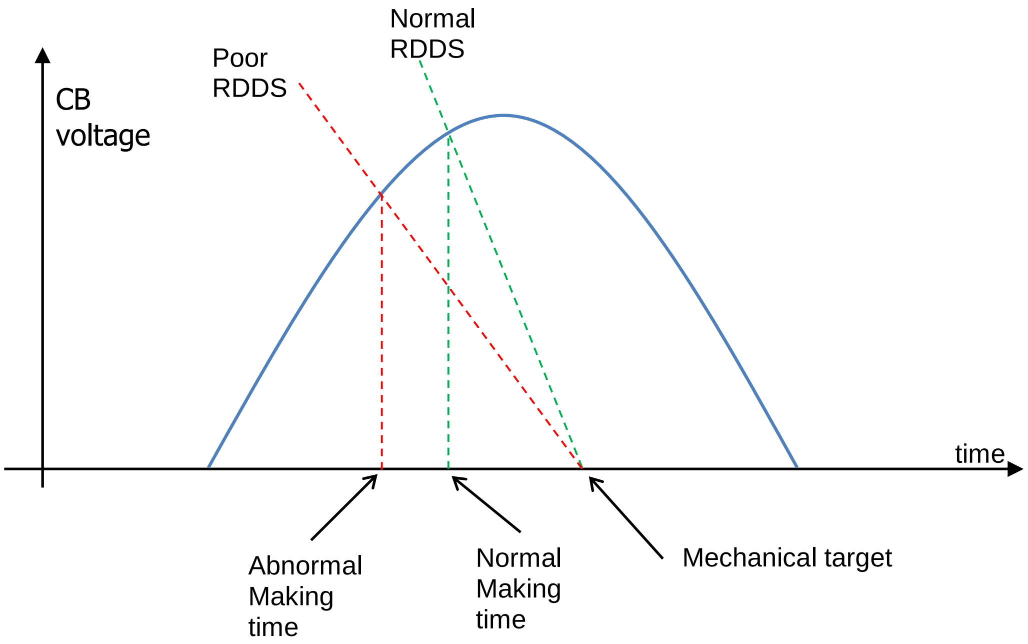


Figure 6-2: Normal/abnormal making times along with consistant mechanical time

6.12.4 Arcing Time Monitoring

As the CSD duty during opening is to control the contact separation time, and the circuit breaker currents are recorded, the CSD is able to estimate arcing times. Hence, deviations between the expected value and measured value may be detected.

In a more basic approach, a simple observation of current interruption sequence could be enough to detect abnormal situations. For instance, in a grounded neutral system, the current zero sequence should be spread each 60°.

6.12.5 Environmental Influence

6.12.5.1 Influence of Auxiliary Voltage

Due to the highly inductive nature of actuators used to trigger circuit breaker operations (electro-magnetic), the auxiliary voltage values have an influence on the total operation time and are therefore measured by the CSD.

This is an indication of the health of the power supplies (usually batteries) of the substation.

6.12.5.2 Influence of Ambient Temperature

Low temperatures may have a slowing effect on circuit breaker operation times and are, therefore, measured by CSD.

7. CONCLUSION

To clarify the process of condition monitoring, some terms are defined. A diagnostic method takes some measured physical parameters of the switchgear and produces some condition indicators, which are used for diagnosis and, later on, when making a decision about the maintenance of the switchgear. The notion of non-intrusive diagnostics is defined according to a scale consisting of:

1. Non-intrusive: The switchgear is not affected.
2. Minimally intrusive: No major tests or repairs are required before returning to service.
3. Intrusive: Tests are necessary before returning to service.

The intrusiveness is considered for both the switchgear and the grid, and during installation and during operation. The usefulness and the degree of maturity are also defined, the latter as a modification of the Technology Readiness Level (TRL).

55 condition assessment methods for switchgear are presented. The majority of them can be used for both MV and HV switchgear. They are routinely being deployed in newly manufactured switchgear, so the equipment is becoming "smarter" out-of-the-factory. But there is still plenty of legacy equipment in the field to operate and maintain, and it's desirable to preserve that gear as long as it remains functional. Many of these techniques/methods can be deployed, but it still takes some knowledgeable engineers to interpret the non-intrusive measurements and decide the best course of action.

The discussed methods were classified into three different categories according to the part of the switchgear that is measured: primary path (contacts, switching and isolation), mechanical parts (both mechanical linkage and driving mechanism), and control and auxiliary circuits.

A comprehensive table classifies the methods according to the physical parameter measured. The table includes the intrusiveness, the degree of maturity, the voltage level, and the insolation and switching medium. Then every method is described in detail with the application, the theoretical background, and the ease of use and the constraints. Many of the methods are very mature, however, for example, most of the methods that investigate the condition of the vacuum in a vacuum circuit breaker are still in the investigation phase.

The actual utilization of non-intrusive diagnostics has been depicted by two means: an international survey conducted by the JWG and a selection of recent case studies found in the literature. The survey included questions about the methods used for condition monitoring. The case studies show how different methods are applied. Non-intrusive diagnostics are often based on indirect measurement of some physical phenomena (ex. radiated UHF signal generated from a partial discharge). Therefore, a lot of effort is required to process and analyse measuring data. Non-intrusive diagnostics allowed in some cases the avoidance of major failures by detecting on time a malfunction or the beginning of degradation and the scheduling of maintenance based on the actual condition of the switchgear.

The closer knowledge the user has about the condition indicators to be assessed and their typical failure modes, the easier the selection of the non-intrusive method and its evaluation. Several failure modes are presented for a live tank high voltage circuit breaker. Three main cost elements have been identified: investment in the non-intrusive method, maintenance costs with and without the non-intrusive method and failure/outage costs with and without the non-intrusive method. The cost calculation contains several values that should be set by the user, as some costs are difficult to estimate or to quantify, as the cost for outage.

Finally, some trends of the development of condition-monitoring methods for circuit breakers are summarised, such as monitoring of new isolation gases, further development of partial discharge diagnostics and antennas to get electromagnetic emissions from different parts of the switchgear.

APPENDIX A. DEFINITIONS, ABBREVIATIONS AND SYMBOLS

A.1. TERMINOLOGY

Condition indicator (of switchgear) – quantitative or qualitative value (parameter) related to the condition of one part or one function of switchgear

Condition measurements (on switchgear) – all kind of measurements of physical values that could be used to assess the condition indicator of switchgear

Condition (of switchgear) – physical state or operational parameters (IEC 60050 §192-06-28) of one module or overall which takes into account its aged state as well as any inherent faults (CIGRE B3.12)

Note 1: It refers the knowledge about switchgear (design details, context of operation, etc.), failures mode analysis (including FMEA), standards, and expert's knowledge

Note 2: Condition classifications: normal, aged but normal in service, defective, faulty, failed

Cost of diagnostic method is a total of expenses and effort needed to use the method

Diagnosis – discovery and naming of what is problematic:

1. the act of identifying a problem by examining something, analysis, examination, investigation, scrutiny
2. a statement or conclusion that describes problem, interpretation, opinion, pronouncement
3. as verb: to diagnose–to recognize by examining, to find the cause of a problem

Diagnosis of electrical equipment (after CIGRE B3.12) – a decision aid tool for**:** maintenance (postponing or advancing preventive maintenance, troubleshooting), residual life evaluation (prognosis, can we rely on equipment), and load (duty) withstand evaluation (achieving optimum, increasing or reducing)

Note 1: Diagnosis may rely on many diagnostics and any available data.

Note 2: In practice, diagnosis based on non-intrusive diagnostics almost always is hypothetical i.e. involves some confidence level and, consequently admits risk, which is more and more accepted in asset management.

Diagnostic – adjective: relating to, or used in diagnosis

Diagnostics – the skill or practice of identifying problems, methods used for diagnosis, "diagnostics" is similar to "diagnostic method"

Diagnostic method (of switchgear) – technology (technique) to obtain one or many condition indicators, it may include diagnostic test, condition measurement, examination, signal processing, data analysis, software and firmware, etc., as well as the resulting condition indicators (chapter 3)

In-service diagnostic method of switchgear – the method which is applied while the switchgear remains on the grid and can operate normally (can perform his duty)

Note: Usually the diagnostic methods require that the measurements are taken during the switchgear operations; in some cases the switchgear should be exercised (forced to operate)

Inspection – documentation of machines operational status, recommendations to ensure proper operation

Integrity of switchgear – its capacity to operate within the ratings assigned by the manufacturer without any constraints

Intrusive intervention on switchgear – any intervention on switchgear which does not guarantee that the integrity of the switchgear is preserved;

Note 1: Any operation of the switchgear prescribed in the equipment manual is considered as **non-intrusive** (i.e. opening, closing, powering within the normal range, normal current carrying, etc.)

Note 2: Minimally intrusive – minor intervention or intervention limited to auxiliary subsystems, no major test required after intervention

Note 3: Intrusive – major intervention involving vital parts of switchgear, tests or studies required after intervention

Note 4: Intrusive methods are off-service

Maintenance – required minor adjustment work to ensure safe and reliable operation. Consumables (sealing, oil) might be exchanged and moving parts greased.

Non-intrusive diagnostic method of switchgear – the method which requires only the non-intrusive interventions, switchgear can be returned to the grid without any further verification

Non-intrusive intervention on switchgear – the intervention which preserve the integrity of the switchgear

Off-service diagnostic method of switchgear – installed or applied when switchgear is temporarily disconnected from the grid

Note: In CIGRE TB 462 in-service and off-service are rather referred as on-line and offline. In this brochure on-line and offline refer rather the remote telecommunication link

Overhaul / Refurbish – replace essential parts, asset gets partly or complete disassembled, restoration of original condition

Usefulness of diagnostic method – a comparison of its value versus its cost, i.e. its cost-effectiveness

Value of diagnostic method - the information i.e. condition indicators and potential diagnosis one can get using the method

A.2. ABBREVIATIONS

AA	Active antenna
AC	Alternating current
AE	Acoustic emission
AIS	Air Insulated Switchgear
ANN	Artificial Neural Networks
ANSI	American National Standards Institute
AR	Augmented Reality
ATC	American Transmission Company
BDV	Breakdown voltage
BLE	Bluetooth Low Energy
CA	Condition assessment
CAN	Controller Area Network
CAPEX	Capital expenditure
CB	Circuit Breaker
CBA	Cost Benefit Analysis
CBM	Condition Based Maintenance
CBRM	Condition Based Risk Management
CIGRE	Conseil International des Grands Réseaux Electriques (Council on Large Electric Systems)

CIRED	Congrès international des réseaux électriques de distribution (International Conference on Electricity Distribution)
CM	Corrective Maintenance
CSD	Controlled Switching Device
CSM	Current sensor measurement
CT	Current Transformer
DC	Direct current
DCM	Dynamic capacitance measurement
DCRM	Dynamic Contact Resistance Measurement
DFR	Digital Fault Recorder
DGA	Dissolved Gas-in-oil Analysis
DPR	Digital Protection Relay
DRM	Dynamic Resistance Measurement
DTW	Dynamic Time Wrapping
EHV	Extra high voltage
EM	Electromagnetic
EMC	Electromagnetic compatibility
EPRI	Electric Power Research Institute
FI	Fault interrupters
FMEA	Failure Mode and Effects Analysis
FS	Full scale
GAAP	General Accepted Accounting Principles
GCB	Generator circuit-breaker
GIS	Gas Insulated Switchgear
GS/s	Giga-Samples Per Second
GST	Grounded-Specimen Test Mode
HF	Hydrogen fluoride / High frequency
HV	High Voltage
HVCB	High Voltage Circuit Breaker
IDT	InterDigital Transducers
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineers
IR	InfraRed
IR	Insulation Resistance
JWG	Joint Working Group
KPI	Critical Performance Indicator
LCC	Life Cycle Cost
LOV	Lost Opportunity Value
LTE-M	Long Term Evolution (4G), category M1

LV	Low Voltage
MEMS	Microelectromechanical Systems
MTS	Mixed Technology Switchgear
MV	Medium Voltage
NDIR	Non-Dispersive Infrared Sensor
NICAM	Non-Intrusive Condition Assessment Methods
NPV	Net Present Value
NSDD	Non Sustained Disruptive Discharges
OC	Over Current
OCB	Oil Circuit Breaker
OEM	Original Equipment Manufacturer
PA	Passive antenna
PC	Personal computer
PD	Partial Discharge
PIN	Positive-Intrinsic-Negative
PMU	Phasor Measurement Unit
PQM	Power Quality Monitor
PTFE	Polytetrafluoroethylene
RBM	Risk based maintenance
RCM	Reliability Centered Maintenance
RDDS	Rate of Decrease of Dielectric Strength
RF	Radio frequency
RFID	Radio frequency identification
RH	Relative Humidity
RVDT	Rotary Variable Differential Transformer
SAW	Surface Acoustic Wave
SER	Sequence of Event Recorder
SPO	Single Pole Operated
T&D	Transmission and Distribution
TB	Technical Brochure
TBPM	Time Based Preventive Maintenance
TCD	Thermal Conductivity Detector
TCM	Trip Coil Monitor
TEE	Transient Electromagnetic Emission
TEV	Transient Earth Voltage
TOR	Terms of references
TPO	Tandem Pole Operated
TRL	Technology Readiness Level
UHF	Ultra High Frequency

UST	Ungrounded-Specimen Test Mode
VHF	Very High Frequency
VI	Vacuum Interrupter
WG	Working Group

APPENDIX B. LINKS AND REFERENCES

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APPENDIX C. SENSORS REVIEW

C.1. INTRODUCTION

Sensors for HV and MV switchgear in order to do monitoring and diagnostics require a certain performance and accuracy. The reason is that this type of equipment is most of its time in a steady state and therefore no actual diagnostics can be done during that time, except for aging over time. In case of an operation the sensor need to capture, during this single occurrence, with highest accuracy any data. Also the sensor itself must have a high reliability in order not to appear as the weak part in the Monitoring and Diagnostic chain.

Another category of sensors are temperature sensors mostly used at the connection points, like spouts, cable connectors, busbar interconnections for observing weak connections. In that case the temperature gives an indication at low currents. In case of a deviation from the standard, some prognostic calculation for nominal currents can be done. If so, an early warning will be given. Temperature observation of the conductive parts inside gas compartments is more difficult. Also the temperature rise on HV is more difficult as of low currents. Therefore the method is more used in MV and LV systems

Several sensors can be considered as non-intrusive methods for Monitoring and Diagnostics in MV and HV switchgear.

C.2. SENSORS USED IN HV SWITCHGEAR

ABLATION SENSORS TECHNOLOGIES

Ablation is measured by checking the resistance between the closed contacts. One method is to apply a high frequency signal to the mains and check the impedance of the contacts in the system by looking at the degradation of the signal response. The value can be compared to the standard value and its deviation is then the degree of the contact ablation.

GAS DENSITY MONITORING SENSORS

Traditionally, density contacts or density meters are used to interfere with control circuitry in order to detect for lockout condition (low density) impairing the breaker capability to interrupt a current.

For pure gas monitoring, pressure and temperature sensors are used to compute density (given knowledge of gas type and gas state equation), to compare density to thresholds (refilling, lockout), to compute trends (advanced warnings), to detect liquefaction risk at low temperatures, to compute annual losses…

These sensors are now available with numerical interfaces (field busses like RS485, CAN…) allowing for multi-measurements in a single sensor (multiplexing). The density computation is often made locally in rugged electronic devices.

As electronic customer acceptance becomes higher, there is a trend to replace traditional density contacts with such electronic systems, in control circuit.

The accuracy of such gas sensors can fall below 0.4% FS (full scale) allowing, with relevant algorithms, to compute annual gas losses.

Figure 7-1: Numerical sensor (on the left, pressure + temperature) with analogue sensor (pressure, 4-20mA) installed on bottom of AIS 245kV circuit breaker

MAIN PRESSURE SENSORS TECHNOLOGIES FOR GAS MONITORING:

- Piezo-resistive : the resistor value of a piezo material changes according to the mechanical force. The resistor value is measured with a bridge arrangement.
- Capacitive : the capacitance of a cavity changes according to inter electrodes length which varies along with mechanical force. The capacitance is measured with a LC self-oscillating circuit.

GAS HUMIDITY SENSORS (DEW POINT):

A mirror is permanently kept cooled and optical sensors monitor the amount of reflected light, proportional to the amount of liquid water condensed at the surface of the mirror. Particular attention shall be kept regarding robustness toward SF_6 decomposition gases.

DYNAMIC PRESSURE SENSORS:

The technology is mainly piezo electric (extended bandwidth). These are only AC measurement, requiring a pre conditioner circuit, charge amplifier: the electrical charges (Coulomb) are converted to voltage in a feedback capacitor across an operational amplifier. The low cut off frequency is chosen by the resistor in parallel to the capacitor.

OPTICAL POSITION SENSORS (CIRCUIT BREAKER):

This is mainly optical slot sensors applied to the output shaft of the drive. These sensors exhibit a better consistency and accuracy than traditional auxiliary contacts which are often subjected to long term drifts due to repeated mechanical efforts.

PRIMARY CURRENT SENSORS, ROGOWSKI TYPE:

Rogowski coil is a particular type of current transformer, without magnetic core. Therefore, the sensitivity is much lower but there is no magnetic saturation effect. Most often, the output is connected to relatively high impedance electronics and the output signal is therefore a (small) voltage proportional to the derivative of the current (di/dt). This type of sensor may be used to measure power frequency currents but it is also well adapted to fast transients, as the bandwidth can be very high, several MHz (only limited by stray capacitances).

Typical applications include replacement of conventional current transformers, quality metering (harmonics), NSDD (Non Sustained Disruptive Discharges) measurement, internal arc localization (GIS), restrike detection, accurate measurement of circuit breaker arcing time.

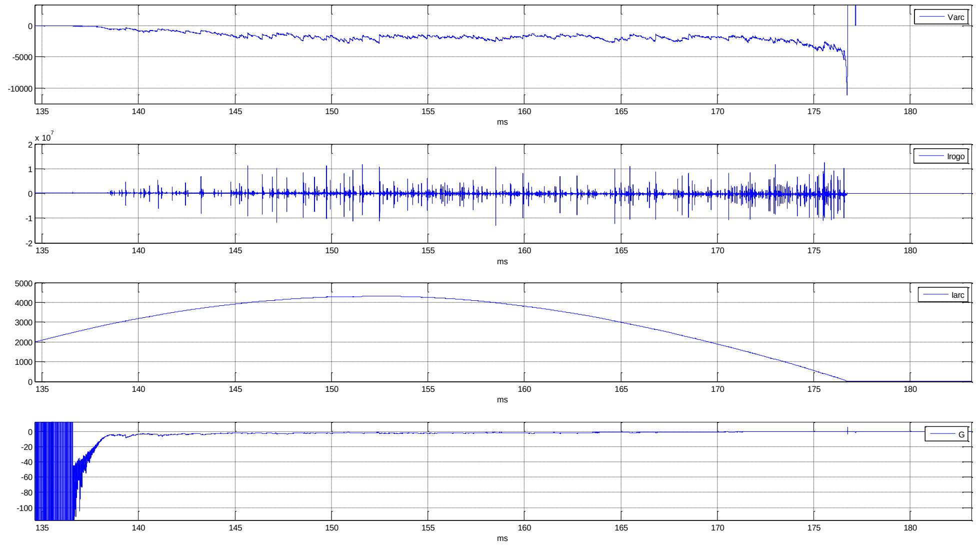


Figure 7-2: Arc voltage, arc current (Rogowski raw signal), arc current (Rogowski integrated), arc conductivity

C.3. SENSORS USED IN MV SWITCHGEAR

IR TEMPERATURE SENSOR

The IR radiation is detected by a thermopile sensor, in which the change in resistance is linear with the temperature. The accuracy, speed of detection, and the dynamic range of the measurement can justify the cost of these sensors. When using IR sensors, it is important to review how they are built into the equipment to be measured. In particular, the temperature of the surrounding environment must be correctly captured; otherwise the temperature measured in the equipment can be misleading.

Figure 7-3: Integrated IR temperature sensor

Figure 7-4: IR-Sensor element

FIBER GUIDED IR TEMPERATURE SENSORS

Another method to measure temperatures on the live parts, is using optical fibers to transfer the IR radiated waves to an IR detector. This might be used for applications where the "line of sight" is missing, i.e. inside spouts. The method is rather costly as the fibers have to have low losses in the IR range and the detector has to be an InGaAs PIN fotodiode. Beside the high cost, the sensitivity at lower temperatures <40°C is very low and the signal to noise ratio is low, therefore the method is inaccurate at low temperatures.

Figure 7-5 Left: Fiber guided IR sensor Right: Fiber mounted to the contact arm

SAW TEMPERATURE SENSORS

Passive sensors in form of an reflective antenna mounted at the point of interest. The antenna is dimensioned to detect a certain frequency. If the temperature changes also the dimension of the antenna changes as it is mounted on a temperature sensitive substrate. A second remote system (IDT = Interdigital Transducer) is radiating a wideband signal which partly the gets reflected from the antenna. The frequency and parts of it which is reflected by the antenna, is the linear to the temperature change. The number of sensors one can have in a system, is limited by the bandwidth the system is allowed to be use.

These sensors can also be used in generator circuit breaker environment (low voltage / high current) for which contact temperature is an issue.

It can also be used for AIS high voltage disconnectors where the antenna is located at ground level. The range of action is a few meters.

RFID TEMPERATURE SENSORS

A simple and cheap solution is the application of RFID technology for temperature measurements. In this case, the sonsored is powered wirelesly and returns the measured temperature. Long term reliablity of this solution should be verified.

Figure 7-6: Wireless sensors installed on the MV circuit breaker stabs

CONTACT FORCE

Strain gauges can be used to measure the contact force in the kinematic chain of the apparatus. From the recorded result several failure modes can be derived.

ANGLE TRAVEL SENSORS (ROTARY ENCODERS)

Rotary sensors are mainly applied to the shaft of the breaker drive. The acquired data from them creates a traveling curve which one would have to interprete.

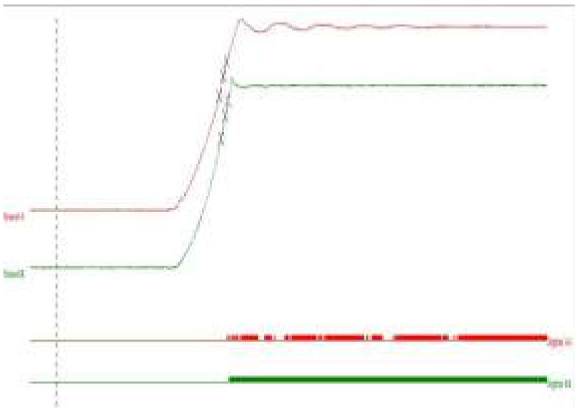


Figure 7-7: Rotary encoder (red) and linear contact force (green) while breaker operation

Most often, the travel curve obtained from these sensors (located in the drive) has to be converted to a chamber displacement by a non-linear function.

From the travel curve some important parameters can be calculated like speed of the contact, stroke, contact bounce, etc... Typically it is measured in synch with other signals like primary current, auxiliary contacts and actuation coil current.

Sensors technologies:

Magnetic (RVDT: variable coupling between two windings of a transformer): robust to different environment constraints but may be sensible to extreme magnetic fields, especially in GCB environment.

Optical (absolute or relative incremental) : the measuring principle is based on an optical disk and optical slot sensor. The immunity to magnetic field is better (limited by internal electronic) but the mechanical robustness is often lower.

Resistive: less often used for online application because of possible wear after numerous operations.

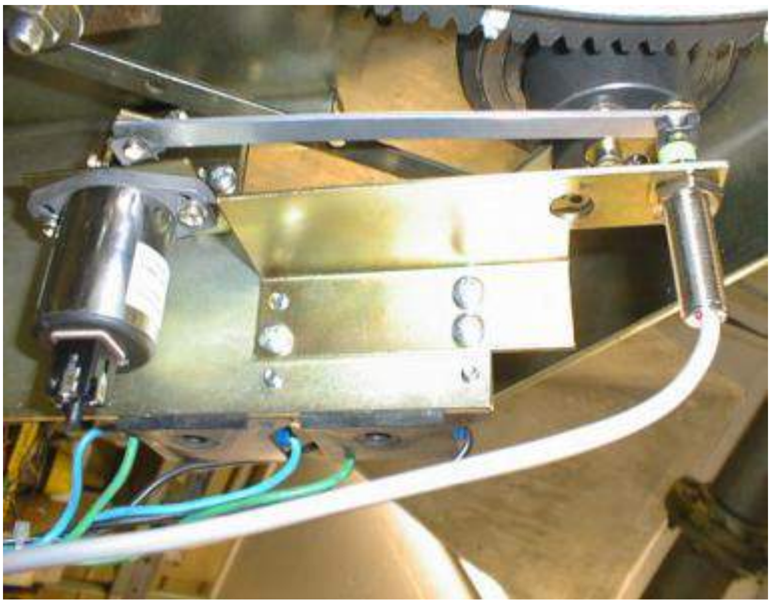


Figure 7-8: Rotative 4-20mA travel curve sensor in drive

C.4. INTRODUCTION

The technical requirements, needs for monitoring and applicable monitoring techniques may be different from one switchgear technology to another.

This section describes and illustrates the different types of switchgear, from medium to high voltage. The aim is to bring a clear illustration of rational monitoring techniques that may be applied, by focusing on the different technical and economic constraints.

C.5. SENSORS USED BOTH IN HV AND MV SWITCHGEAR

Sensors which are in common for both switchgear are related to analyse operation time in most cases.

VIBRATION SENSOR

They are mostly used by applying acceleration sensors and one can find them in smart phones. They are quite cheap as components but they need to be integrated to the switchgear and to be interconnected to the monitoring system.

PD MEASUREMENTS

PD can be detected as HF signal, capacitively coupled signal or acoustic wave. The interpretation of these signals is rather difficult as they are dependent on other parameters including: environmental conditions, construction, and material.

Figure 7-9: UHF capacitive sensor (external reference sensor)

The sensors may be internal or external (GIS insulator flanges).

The UHF method (capacitive antennas) method measures the RF spectral activity but the main difficulty is still to correlate this UHF activity to absolute picocoulomb value for online monitoring systems.

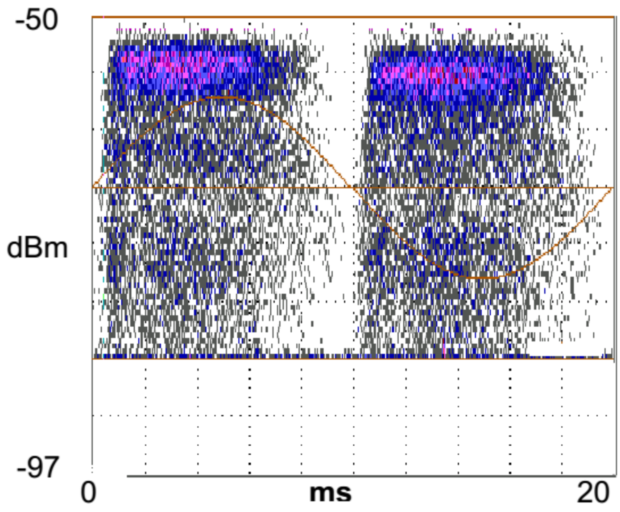


Figure 7-10: UHF activity time signature

ACCELERATION SENSORS

Today there are cheap electronic acceleration sensors in smartphones and in airbags in cars. Also here, the interpretation of the signal is a key to usefulness.

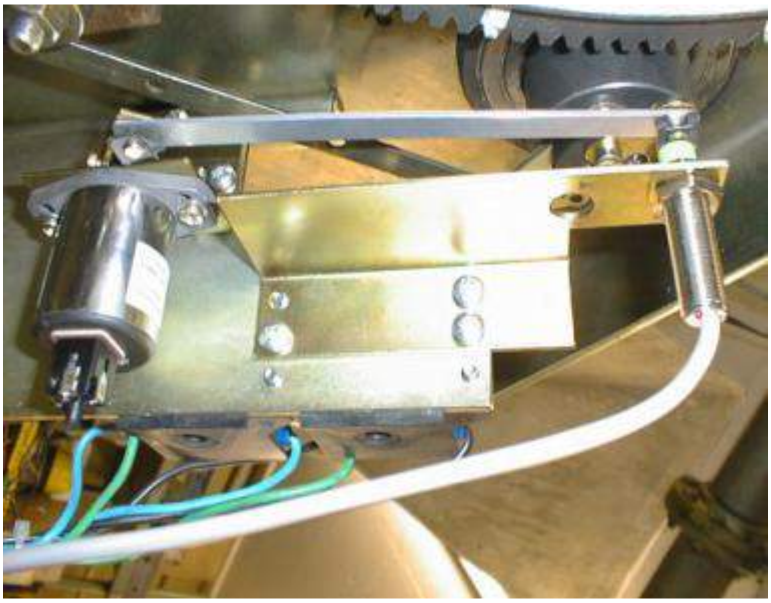


Figure 7-11: Rotative 4-20mA travel curve sensor in drive

AUXILLIARY CURRENTS SENSORS

In order to measure both DC and AC currents Hall effect sensor are used. Typical application includes measuring actuation coil current.

Advantages:

- Contactless, DC+AC

Drawbacks:

- residual magnetic flux in the magnetic core, leading to residual/variable signal offset which may be compensated by appropriate processing.
- Sensitivity to external magnetic field

Technology : a magnetic core with small gap in which is inserted a hall effect material. Two types of sensor exist : closed or open loop arrangement. In closed loop (active) arrangement, an opposite magnetic flux is applied and a regulation is operated in order to nullify the total flux at every time : "zero-flux" technology (more expensive).

C.6. SUMMARY

Sensors used in HV switchgear needs to have a higher performance in terms of isolation to the mains. That requires different methods also which then result in a higher cost for sensor and system.

From system cost view point, the sensor part is a bigger portion this is also because a comprehensive system needs more than one sensor, with dedicated requirements described in this chapter, to generate useful information about the condition of the assets.

Technologically, sensors getting cheaper and also more integrated, as IoT is driving the market. In the field of application for HV and MV this advantage can only party get used due to high performance and isolation requirements. In many cases optical or wireless technologies have to be used, which is challenging.

APPENDIX D. SWITCHGEAR REVIEW

D.1. HV SWITCHGEAR

GAS INSULATED SWITCHGEAR

All active parts are located at ground level and insulated from ground potential by the help of metallic enclosures. A specific insulation media (gas…) is used to guarantee sufficient insulation level (including surge insulation level) between active parts and enclosure. The metallic enclosures are grounded by regularly spaced grounding links, ensuring for safe operations ("touch potential").

The cost of such technology is much higher than others, and it is therefore used when land area is an issue (cities…) or when environmental conditions are too harsh.

One of the main issues of such a switchgear type is the possibility of internal fault between active parts and enclosure (internal arc), due to failure of insulation media (typically gas, SF_6 or recent alternatives).

Therefore, the monitoring of insulation media is of key importance. Traditional approaches include gas density monitoring and partial discharges monitoring.

The number of gas compartments can be rather high in a unique installation : as each of them has to be monitored, the total number of sensors can be high.

Also, as the quantity of insulation gas (SF_6, global warming effect) is much higher in this technology than in other switchgear type, the regulatory constraints emphasize the need for annual losses measurement.

Logically, the high cost level of the GIS technology has historically contributed to the development of monitoring techniques: ratio between monitoring system (electronics + sensors) cost and switchgear cost is low.

Most often, in a given substation, a unique manufacturer delivers all GIS parts (there is no standard allowing to connect switchgear from different manufacturers). Therefore, monitoring systems are sometimes specific to the GIS manufacturer design, developed and delivered by the manufacturer, and therefore not generic.

Figure 7-12: Typical 400kV GIS indoor installation

Figure 7-13: 400kV GIS connection to overhead lines (bushings)

AIR INSULATED SWITCHGEAR - LIVE TANK

All active parts are isolated from each other and from ground potential by air distance. The cost of such technology is now quite low. As a consequence, there is also a trend for lower cost monitoring systems.

For a circuit breaker, only the interrupting chamber is sealed and filled with gas (which contributes both for dielectric withstand and for current interruption). Disconnectors operate in the air.

Environmental outdoor and online monitoring systems shall withstand outdoor temperature. Most often, they are installed in local cubicles (marshaling boxes, circuit breaker drives…). If the monitoring system is installed on the breaker frame or inside the drive, it shall also withstand shocks and vibrations. With additional electromagnetic interferences (especially disconnectors operations), this is a rather harsh environment.

Often, switchgear from different manufacturers may be found in a unique substation, which reinforces the need for generic and non-intrusive monitoring solutions.

Figure 7-14: 420kV AIS substation (dual chambers circuit breakers)

Figure 7-15: 420kV AIS circuit breaker and disconnectors

Figure 7-16: 145kV AIS substation (single chamber circuit breaker, single drive)

AIR INSULATED SWITCHGEAR - DEAD TANK

In this particular case, the circuit breaker is located at ground level and is connected to active parts by the help of bushings. It is very similar to a GIS circuit breaker (grounded metallic enclosure).

The main advantage of such particular arrangement is to facilitate maintenance.

Figure 7-17: 550kV dead tank circuit breaker

GENERATOR CIRCUIT BREAKERS

This particular type of circuit breaker (can also be considered as medium voltage) is located in power plants between generator and step-up power transformer. Nominal voltage is low (tens of kV), but current is high (up to 30kA, short circuit above 200kA). Due to the high nominal current value the main concern for this type of circuit breaker is the temperature:

- Temperature of main contacts. Wireless measurement techniques are available.
- Fans monitoring, if forced cooling

Extreme values of fault currents impose particular precautions for electronic devices located in the vicinity (robustness towards magnetic field).

Figure 7-18: Air-insulated switchgear

D.2. MV SWITCHGEAR

Medium voltage circuit breakers, automatic reclosers, and fault interrupters are situated in both substations and along the distribution feeders through the network. Due to the desire for network segmentation for fault isolation, these devices are much greater in number compared to the high voltage equipment. Because of their greater number, lower power, and relatively lower impact to system reliability, the medium voltage equipment is more sensitive to price. Time-based maintenance programs for these devices are usually more limited or non-existent, especially for equipment outside of the substation. In some locations, the devices are installed and are not inspected during their lifetime, with the expectation that it will merely be replaced after reaching end-of-life. With increasing scrutiny on system reliability, there is more demand for cost effective condition monitoring techniques that allow condition-based maintenance programs to be implemented for these devices on the medium voltage system.

Medium voltage systems are typically classified as overhead (line-connected) or underground (cable-connected), with the former exhibiting a higher prevalence of faults due to the exposure of the lines to animals, vegetation, and the public. Cable-connected systems are less prone to these fault causes since cables are buried, but they are also more expensive to install.

Medium voltage circuit-breakers, automatic reclosers, and fault interrupters employ a variety of interrupting media (air, vacuum, SF_6, oil) and dielectric media (air, SF_6, oil, solid material), though vacuum interrupters have high penetration at these voltage levels. These devices typically have their own stand-alone relay system, and can be operated locally or remotely.

Instead of installing dedicated condition monitors in this equipment, a popular method to quickly assess device health is via infrared camera inspection. This may or may not be part of a routine maintenance program. In some other cases, devices with communication capability have condition monitors installed during manufacturing and can report alarms if any performance criteria are not met during operation.

MEDIUM VOLTAGE EQUIPMENT IN THE SUBSTATION

Figure 7-19: Air-insulated circuit breaker with vacuum interrupters

Figure 7-20: Air-insulated circuit breaker with vacuum interrupters and magnetic actuators

Figure 7-21: Gas-insulated switchgear

Figure 7-22: Air-insulated switchgear

MEDIUM EQUIPMENT OUTSIDE THE SUBSTATION

Figure 7-23: Pad-mounted, gas insulated switchgear

Figure 7-24: Gas-insulated switchgear

Figure 7-25: Vault-mounted, gas insulated switchgear

Figure 7-26: Vault-mounted switchgear with solid dielectric insulation

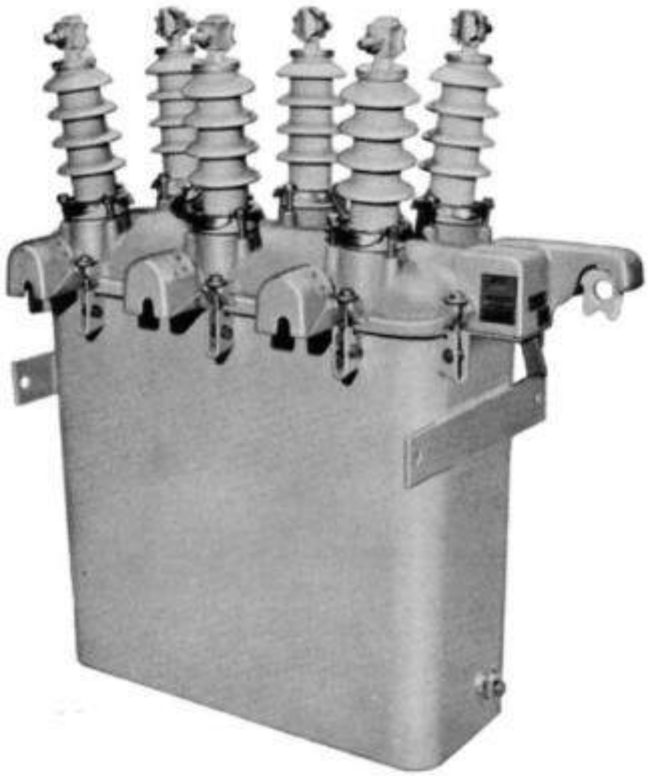
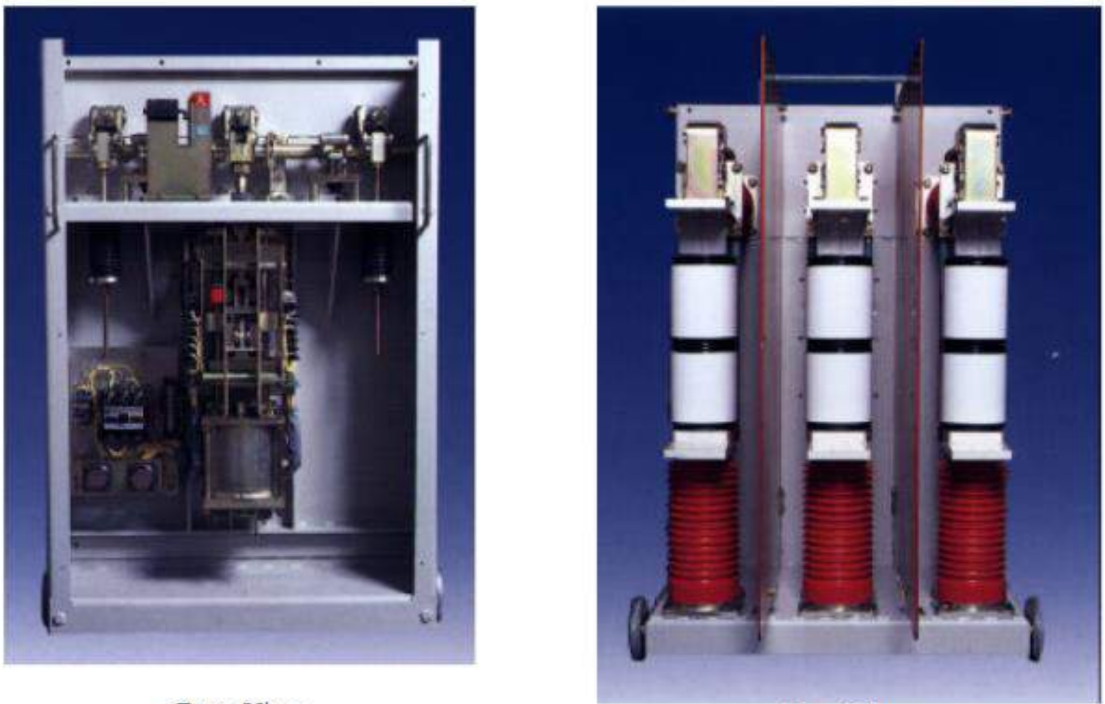


Figure 7-27: Overhead hydraulic recloser with oil insulation

Figure 7-28: Overhead recloser with vacuum interrupters and integral power modules & sensors

MEDIUM VOLTAGE COMPONENTS



Front View　　　　Rear View

Figure 7-29: Draw-out circuit breaker with vacuum interrupters

Figure 7-30: Vacuum interrupters

D.3. SUMMARY

Some differences exist between monitoring systems dedicated to the different switchgear technologies. Generic monitoring methods using non-intrusive methods are applicable to different switchgear types.

APPENDIX E. SURVEY

E.1. INTRODUCTION

A survey was compiled and sent to Consultants, Industry, Maintenance Service providers, Manufacturers and Utility representatives worldwide to determine current and future trends of non-intrusive diagnostics. Following detailed discussions within the WG it was decided to use a web survey tool to capture the data from the various different representatives worldwide.

The survey was split in to three voltage levels: ≤38 kV, >38 kV to ≤170 kV and >170 kV. All respondents were promised to be provided with the survey results when the working group had finished analyzing the information obtained.

The survey consisted of an introduction, company details and 3 sections. In Section 1 respondents were provided with a list of circuit breaker types to select from. Following the selection of applicable circuit breaker types the respondents were asked to select from four types of maintenance activities and also indicate the number of units their answers were based on for each type.

The maintenance activity types were:

Time based preventive maintenance (TBPM)

Condition based maintenance (CBM)

Reliability centered maintenance (RCM)

Corrective maintenance (CM)

Section 2 of the survey dealt with "Non-Intrusive Diagnostic Techniques". Depending on the circuit breaker types selected previously, the next set of questions related to diagnostic techniques applicable to that circuit breaker. Respondents were asked to answer on whether the technique they used was "In-service" or "Off-service", how frequently they monitored the data, how they responded to alarms and also how mature the technique was within their company. Finally in this section each technique had to be rated on "ease of use" and "ease of analysis of data".

The last section asked the respondents to rate the importance of "cost", "performing tests on equipment remaining in-service" and "performing tests on equipment without dismantling" from their company's perspective.

E.2. SURVEY QUESTIONNAIRE

The questionnaire was compiled as follows:

Introduction

This survey is facilitated by Cigré/CIRED A3.32 JWG Non-intrusive methods for condition assessment of T&D switchgears to better understand current condition assessment practices in Power Industry.

A3.32 Working group was formed to investigate many emerging non-intrusive technologies that are reported in the literature, most of them allowing in-service evaluation (for example: partial discharge detection, dynamic resistance measurements, gas leak detections, vibration measurements, etc…). The working group will review the current and future trends of non-intrusive diagnostics – especially in service – in both Medium Voltage and High Voltage switchgear equipment. This part of the research is to gather user feedback and experience/future needs from utilities regarding condition assessment.

Therefore, we are asking for your opinion in a small scale inquiry to users with some relationship to the WG members.

After each question, there is an opportunity to provide any additional comments if you want to complete your answer with further details. Please add as many comments as possible.

We request you to finalize this survey before June 30th, 2015.

After finalization of the survey, you will personally receive the results. Your company's name will not be disclosed within the Working Group nor will it be used for any commercial activity.

On behalf of the Working Group I thank you for your cooperation.

Nenad Uzelac
Convenor Cigré/CIRED JWG A3.32

Company Name: _______________

Department Name:*(Please select)*

Distribution, Transmission, Engineering, Maintenance, Other

Company Profile: *(Please select)*

Utility, Manufacturer, Consultant, Maintenance Service, Industry, Other

Company Size: *(Please select)*

< 100 employees, 100 – 1000, 1000 – 5000, >5000

Country:_______________

Section 1

Please select voltage level:
≤38kV, >38kV to <170kV, >170kV

Which types of circuit breaker does your company operate? Number of units installed?

Type	Number of units installed

Metal-clad	1-10, 11-100, 101-300, 301-1000, >1000
Metal-enclosed interrupter	1-10, 11-100, 101-300, 301-1000, >1000
Underground SF_6 switches	1-10, 11-100, 101-300, 301-1000, >1000
Underground vacuum switches	1-10, 11-100, 101-300, 301-1000, >1000
Overhead SF_6 switches (pole-top)	1-10, 11-100, 101-300, 301-1000, >1000
Overhead vacuum switches	1-10, 11-100, 101-300, 301-1000, >1000
Bulk-oil	1-10, 11-100, 101-300, 301-1000, >1000
Minimum-oil	1-10, 11-100, 101-300, 301-1000, >1000
Air-blast	1-10, 11-100, 101-300, 301-1000, >1000
Live-tank SF_6	1-10, 11-100, 101-300, 301-1000, >1000
Dead-tank SF_6	1-10, 11-100, 101-300, 301-1000, >1000
Other	1-10, 11-100, 101-300, 301-1000, >1000

Which of the following non-intrusive diagnostic techniques are used within your company?

- Insulation test (capacitance and tan δ)
  - In-service, Off-service
- Static Contact Resistance
- Dynamic Contact Resistance
- Contact Wear
  - In-service, Off-service
- SF_6 Quality
  - In-service, Off-service
- SF_6 Gas Density
  - In-service, Off-service
- SF_6 Gas Leak Detection
  - In-service, Off-service
- First Trip
- Coil Current Analysis
  - In-service, Off-service
- Motor Current Analysis
  - In-service, Off-service
- Vibration Analysis
  - In-service, Off-service
- Transient Electromagnetic Emissions Analysis
- Partial Discharge
  - In-service, Off-service
- Radiography
  - In-service, Off-service
- Digital Fault Recordings & Digital Relay Recordings
- Infrared Thermography
- Number of Close/Open Operations
  - In-service, Off-service
- Temperature Measurements
  - In-service, Off-service
- Travel Curve (contact displacement)
  - In-service, Off-service
- Visual Inspections
  - In-service, Off-service
- Vacuum Integrity
  - In-service, Off-service

For each of the above options the following questions followed depending on the respondents selections:

- In-service - Data Monitoring Frequency
  - Continuous, Periodic
- In-service - Continuous - Alarm Response Time
  - Immediate, Within 30 days, Next Outage, Other

- In-service - Continuous - Degree of maturity
  - Investigation, Pilot runs, Standard practice in field
- In-service - Periodic - Data Monitoring Frequency
  - Daily, Weekly, Monthly, Annual, Alarm based
- In-service - Periodic – Maturity
  - Investigation, Pilot runs, Standard practice in field
- Off-service frequency
  - Investigation only, < 1 year, 1-5 years, 5-10 years, >10 years, Alarm based
- Off-service - Degree of maturity
  - Investigation, Pilot runs, Standard practice in field

What is the easiness of use of non-intrusive diagnostic techniques?

- Insulation test (capacitance and tan δ) - In-service
  - Easy, Neutral, Difficult
- Insulation test (capacitance and tan δ) - Off-service
  - Easy, Neutral, Difficult
- Static Contact Resistance
  - Easy, Neutral, Difficult
- Dynamic Contact Resistance
  - Easy, Neutral, Difficult
- Contact Wear - In-service
  - Easy, Neutral, Difficult
- Contact Wear - Off-service
  - Easy, Neutral, Difficult
- SF_6 Gas Quality - In-service
  - Easy, Neutral, Difficult
- SF_6 Gas Quality - Off-service
  - Easy, Neutral, Difficult
- SF_6 Gas Density - In-service
  - Easy, Neutral, Difficult
- SF_6 Gas Density - Off-service
  - Easy, Neutral, Difficult
- SF_6 Gas Leak Detection - In-service
  - Easy, Neutral, Difficult
- SF_6 Gas Leak Detection - Off-service
  - Easy, Neutral, Difficult
- First Trip
  - Easy, Neutral, Difficult
- Coil Current Analysis - In-service
  - Easy, Neutral, Difficult
- Coil Current Analysis - Off-service
  - Easy, Neutral, Difficult
- Motor Current Analysis - In-service
  - Easy, Neutral, Difficult
- Motor Current Analysis - Off-service
  - Easy, Neutral, Difficult
- Vibration Analysis - In-service
  - Easy, Neutral, Difficult
- Vibration Analysis - Off-service
  - Easy, Neutral, Difficult
- Transient Electromagnetic Emissions Analysis
  - Easy, Neutral, Difficult
- Partial Discharge - In-service
  - Easy, Neutral, Difficult
- Partial Discharge - Off-service
  - Easy, Neutral, Difficult

- Radiography - In-service
  - Easy, Neutral, Difficult
- Radiography - Off-service
  - Easy, Neutral, Difficult
- Digital Fault Recordings & Digital Relay Recordings
  - Easy, Neutral, Difficult
- Infrared Thermography
  - Easy, Neutral, Difficult
- Number of Close/Open Operations - In-service
  - Easy, Neutral, Difficult
- Number of Close/Open Operations - Off-service
  - Easy, Neutral, Difficult
- Temperature Measurements - In-service
  - Easy, Neutral, Difficult
- Temperature Measurements - Off-service
  - Easy, Neutral, Difficult
- Travel Curve (contact displacement) - In-service
  - Easy, Neutral, Difficult
- Travel Curve (contact displacement) - Off-service
  - Easy, Neutral, Difficult
- Visual Inspections - In-service
  - Easy, Neutral, Difficult
- Visual Inspections - Off-service
  - Easy, Neutral, Difficult
- Vacuum Integrity - In-service
  - Easy, Neutral, Difficult
- Vacuum Integrity - Off-service
  - Easy, Neutral, Difficult

How easy is it to analyse the results of non-intrusive diagnostic techniques?

- Insulation test (capacitance and tan δ) - In-service
  - Easy, Neutral, Difficult
- Insulation test (capacitance and tan δ) - Off-service
  - Easy, Neutral, Difficult
- Static Contact Resistance
  - Easy, Neutral, Difficult
- Dynamic Contact Resistance
  - Easy, Neutral, Difficult
- Contact Wear - In-service
  - Easy, Neutral, Difficult
- Contact Wear - Off-service
  - Easy, Neutral, Difficult
- SF_6 Gas Quality - In-service
  - Easy, Neutral, Difficult
- SF_6 Gas Quality - Off-service
  - Easy, Neutral, Difficult
- SF_6 Gas Density - In-service
  - Easy, Neutral, Difficult
- SF_6 Gas Density - Off-service
  - Easy, Neutral, Difficult
- SF_6 Gas Leak Detection - In-service
  - Easy, Neutral, Difficult
- SF_6 Gas Leak Detection - Off-service
  - Easy, Neutral, Difficult
- First Trip
  - Easy, Neutral, Difficult
- Coil Current Analysis - In-service

  - Easy, Neutral, Difficult
- Coil Current Analysis - Off-service
  - Easy, Neutral, Difficult
- Motor Current Analysis - In-service
  - Easy, Neutral, Difficult
- Motor Current Analysis - Off-service
  - Easy, Neutral, Difficult
- Vibration Analysis - In-service
  - Easy, Neutral, Difficult
- Vibration Analysis - Off-service
  - Easy, Neutral, Difficult
- Transient Electromagnetic Emissions Analysis
  - Easy, Neutral, Difficult
- Partial Discharge - In-service
  - Easy, Neutral, Difficult
- Partial Discharge - Off-service
  - Easy, Neutral, Difficult
- Radiography - In-service
  - Easy, Neutral, Difficult
- Radiography - Off-service
  - Easy, Neutral, Difficult
- Digital Fault Recordings & Digital Relay Recordings
  - Easy, Neutral, Difficult
- Infrared Thermography
  - Easy, Neutral, Difficult
- Number of Close/Open Operations - In-service
  - Easy, Neutral, Difficult
- Number of Close/Open Operations - Off-service
  - Easy, Neutral, Difficult
- Temperature Measurements - In-service
  - Easy, Neutral, Difficult
- Temperature Measurements - Off-service
  - Easy, Neutral, Difficult
- Travel Curve (contact displacement) - In-service
  - Easy, Neutral, Difficult
- Travel Curve (contact displacement) - Off-service
  - Easy, Neutral, Difficult
- Visual Inspections - In-service
  - Easy, Neutral, Difficult
- Visual Inspections - Off-service
  - Easy, Neutral, Difficult
- Vacuum Integrity - In-service
  - Easy, Neutral, Difficult
- Vacuum Integrity - Off-service
  - Easy, Neutral, Difficult

In your opinion how important is the cost advantage of using non-intrusive diagnostic techniques?
Extremely important, Very important, Moderately important, Slightly important, Not at all important

In your opinion how important is the advantage of performing tests on equipment remaining in service?
Extremely important, Very important, Moderately important, Slightly important, Not at all important

In your opinion how important is the advantage of performing tests on equipment without dismantling it?
Extremely important, Very important, Moderately important, Slightly important, Not at all important

APPENDIX F. MATRIX

ID	Name	Description	Group	Main Category	Sub Category	In- /Off-service	Intrusive (Non, Min, Strongly)	Periodically Continuously	Degree of Maturity	Voltage Level	Switching Medium	Insulation	Reference-Keys
1	Magnetron	Well established measurement during production, no field application. Circuit breaker need to be dismounted for measurements during service life.	Insulation	Insulation Medium	ISO-vacuum quality	Off	Strongly	Per.	Standard practice in the field	MV	VCB	all	Renz2007
2	Mobile Magnetron	based on stationary application of magnetron discharge for pressure determination	Insulation	Insulation Medium	ISO-vacuum quality	Off	Non	Per.	R&D-Activity	MV	VCB	AIS	Eichhoff2013,
3	Dielectric Vacuum Testing	based on breakdown characterstic of vacuum gap, BD-voltage significantly decreases if pressure exceeds critical value, no quantitative measurement, only pass/fail	Insulation	Insulation Medium	ISO-vacuum quality	Off	Non	Per.	Standard practice in the field	HV	VCB	all	Slade2007, Megger2012
4	FE Current Analysis	FE-current measurement after arc-polishing, practical application and evaluation challenging	Insulation	Insulation Medium	ISO-vacuum quality	Off	Non	Per.	R&D-Activity	MV	VCB	all	Frontzek1993, Zadeh2011
5	Arc Voltage Analysis	Analysis of pressure-related spikes in measures arc voltage, limited measuring range	Insulation	Insulation Medium	ISO-vacuum quality	Off	Non	Per.	Theoretical Concept	MV	VCB	all	Merck1999
6	PD measurement	PD pulse acquisition,measurement of apparent charge,evaluation of magnitude, repetition rate,frequency and phase angle, detected by capacitive sensor	Insulation	PD	PD-electrical	In	Min	both	Standard practice in the field	HV+ MV		all	Blokhintsev 2009
7	PD measurement	PD pulse acquisition,measurement of apparent charge,evaluation of magnitude, repetition rate,frequency and phase angle, detected by UHF space and window sensor	Insulation	PD	PD-UHF	In	Non	both	Standard practice in the field	HV+ MV		all	
8	PD measurement	PD pulse acquisition,measurement of apparent charge,evaluation of magnitude, repetition rate,frequency and phase angle, detected by ultrasonic testing	Insulation	PD	PD-ultra sound	In	Non	Per.	Standard practice in the field	MV		Solid-Ins.	Garnett2011

ID	Name	Description	Group	Main Category	Sub Category	In- /Off-service	Intrusive (Non, Min, Strongly)	Periodically Continuously	Degree of Maturity	Voltage Level	Switching Medium	Insulation	Reference-Keys
9	PD measurement	PD pulse acquisition,measurement of apparent charge,evaluation of magnitude, repetition rate,frequency and phase angle, detected by TEV sensor	Insulation	PD	PD-TEV	In	Non	Per.	Standard practice in the field	MV		Solid-Ins.	Garnett2011
10	PD measurement-sniffer		Insulation	PD	PD-UHF	In	Non	Per.	Mature product available	MV	all	Solid-Ins.	Leonard2011
11	Transient electro magnitic emissions	Transient electromagnetic emissions (TEE)are generated from the CB interrupters. Four UHF antennas installed in the vicinity of the CB allow to locate each TEE in an interrupter. By analysing these TEEs over several switching operations, we may deduce relevant information on the CB condition.	Switching	General Diagnostic	Timing of operation+ Restrikes Re-ignitions+ Prestrike delays+ PD-UHF	In	Non	Per.	Prototype available	HV+ MV	VCB+Gas +Oil+Air	AIS	Poirier2010, Moore2004
12	Transient electro magnitic emissions	Transient electromagnetic emissions (TEE)are generated from the CB interrupters. The location of the emitting CB pole is performed by using both high-frequency active antennas and low-frequency passive antennas. By analysing these TEEs over several switching operations, we may deduce relevant information on the CB condition.	Switching	General Diagnostic	Timing of operation+ Restrikes Re-ignitions+ Prestrike delays+ PD-UHF	In	Non	Per.	R&D-Activity	HV+ MV	Gas	AIS	Lopez2012
13	Dynamic contact resistance	The time-varying contact resistance is recorded during the switching operation. The restistance curve gives information on the arcing and the main contacts condition.	Current carrying	Wear	WEAR-Re-sistance	Off	Non	Per.	Commercial product available	HV+ MV	Gas	all	Lalonde2012, Landry2004, Ostojic2013, Landry2008, Stanisic2011
14	Static contact resistance	Main contacts resitance is measured with a micro-Ohmeter while the CB is in closed position	Current carrying	Wear	WEAR-Re-sistance	Off	Non	Per.	Standard practice in the field	HV+ MV	VCB+Gas +Oil+Air	all	Stanisic2011

ID	Name	Description	Group	Main Category	Sub Category	In- /Off-service	Intrusive (Non, Min, Strongly)	Periodically Continuously	Degree of Maturity	Voltage Level	Switching Medium	Insulation	Reference-Keys
15	Vibration analysis	Accelerometers are installed on the CB. Mechanical anomalies can be detected by comparing vibrations signals with reference signatures.	Mechani-cal	Travel	Timing of operation	In & Off	Non	Per.	Tested in the field	HV	VCB+Gas +Oil+Air	all	Beattie1996 Hoidalen2005 Landry2008_1 Lee2002 Runde1999
16	Mechanical timing	The method evaluates the time elapsed between the command signal and the contact part or the contact touch in each interrupter of the CB	Mechani-cal	Travel	Timing of operation	Off	Non	Per.	Standard practice in the field	HV+ MV	VCB+Gas +Oil+Air	all	Rusek2008
17	Contact travel	A motion transducer is mounted on a moving part of the operating mechanism. The contact position is given as a function of time during the switching operation	Mechani-cal	Travel	TRAVEL-rotary (speed, acc,..)+ TRAVEL-linear (speed, acc,..)	Off	Min	both	Standard practice in the field	HV+ MV	VCB+Gas +Oil+Air	all	Brown2012 Lalonde2013
18	Vibration analysis	An accelerometer is attached to a operation driving system of the SF_6 GCBs. The signals are conditioned by a measurement system and analyzed by with a Dynamic-Time-Warping (DTW) algorithm. Mechanical problems can be detected and it is verified with 3 case studies.	Mechani-cal	Travel	Driving system-kinematic chain	In	Non	both	Tested in the field	HV	Gas		Landry2008
19	Current / voltage measurement	Saturation-free non-magnetic current / voltage sensors such as Rogowski Coils, Capacitive & resistive dividers are used for current and voltage measurement of a MV switchgear.	Switching	General Diagnostic	current & voltage measurements + I^2T + PD-RF	In	Non	both	Standard practice in the field	HV+ MV	VCB+Gas +Oil+Air	AIS	Leif_ABB
20	PD measurement	Internal PD couplers installed inside the GIS chambers to detect electro magnetic wave generated by partial discharge.	Insulation	PD	PD-UHF	In	Strongly	both	Standard practice in the field	HV	Gas		ITO_MELCO

ID	Name	Description	Group	Main Category	Sub Category	In- /Off-service	Intrusive (Non, Min, Strongly)	Periodically Continuously	Degree of Maturity	Voltage Level	Switching Medium	Insulation	Reference-Keys
21	PD measurement	External PD couplers installed on the GIS barriers to detect electro magnetic wave by partial discharge coming out from the GIS chamber	Insulation	PD	PD-UHF	In	Non	both	Standard practice in the field	HV	Gas		ITO_MELCO
22	SF_6 gas leakage measurement	SF_6 density of the GIS is measured by a high precision gas pressure sensor with a temperature sensor to compensate to the pressure at 20C deg. By analysing long term trend, it is possible to detect 0.1%/year gas leakage with certainty.	Insulation	Insulation Medium	ISO-leakage	In	Non	both	Standard practice in the field	HV	Gas		Kamei2011
23	Dynamic Re-sistance Measure-ment	A DC source is connected across the open interrupter; the test will be performed under "Close-Open" operation. The voltage and current waveform during the operation gives us a condition of the contact wear.	Switching	Wear	WEAR-Re-sistance	Off	Non	Per.	Tested in the field	HV+ MV	Gas	GIS	inproceedings Lalonde2012
24	Trip/Close Coil Current	Trip and close coil current (CC) signature is an effective and noninvasive parameter in CB online condition monitoring. The failures and their causes are categorized based on the outcome of these investigations.	Control and Acces-sories	AUX	AUX-coil current	In & Off	Non	both	R&D-Activity	HV+ MV	Gas	GIS	article Razi2014
25	Radiographic Inspection	View inside the Vaccum Interrupter	Switching	General Diagnostic	n/a	In	Min	Per.	Tested in the field	HV+ MV	VCB+Gas +Oil+Air	GIS	ABB Review 04/12
26	Temperature Monitoring	Focus on SAW technologies, describing pros and cons	Current carrying	Temperatur e	n/a	In	Non	Con.	Tested in the field	HV+ MV	all	all	Cigre Conference Canada 2010
27	MySiteCare	Complete M&D system for condition based maintenance	Current carrying	General Diagnostic	Timing of operation	In	Non	Con.	Mature product available	HV+ MV	all	all	Deck 2013
28	Coil current	Current measurement during switching operation. Giving information about poor inicialation contacts, resistance to slug movement, delay in the tripping of the latch, faults in the tripping coil, bad, or poorly aligned auxiliary contacts.	Control and Acces-sories	AUX	AUX-coil current	In	Non	Per.	Standard practice in the field	HV+ MV	VCB+Gas +Oil+Air	all	Beattie 1996

ID	Name	Description	Group	Main Category	Sub Category	In- /Off-service	Intrusive (Non, Min, Strongly)	Periodically Continuously	Degree of Maturity	Voltage Level	Switching Medium	Insulation	Reference-Keys
29	I^2T Fault recorders / Digital protection relay	Making analog record of currents and voltages in all three phases and signals like coil tripping. Then processing these records. Trigger condition for making the rcord: CB switching operation, short cut detection, overvoltage, overcurrent, …	Switching	Wear	WEAR-I^2T	In	Non	Con.	Commercial product available	HV+ MV	VCB+Gas +Oil+Air	all	Kopejtko, Kocis 2013
30	Timing of oparation Fault recorders / Digital protection relay	Making analog record of currents and voltages in all three phases and signals like coil tripping. Then processing these records. Trigger condition for making the rcord: CB switching operation, short cut detection, overvoltage, overcurrent, …	Switching	General Diagnostic	Timing of operation+ Restrikes Re-ignitions+ Prestrike delays+ PD-UHF	In	Non	Con.	Commercial product available	HV+ MV	VCB+Gas +Oil+Air	all	Kopejtko, Kocis 2013
31	Restrike, Reignition Fault recorders / Digital protection relay	Making analog record of currents and voltages in all three phases and signals like coil tripping. Then processing these records. Trigger condition for making the rcord: CB switching operation, short cut detection, overvoltage, overcurrent, …	Switching	General Diagnostic	Restrikes Re-ignitions	In	Non	Con.	Commercial product available	HV+ MV	VCB+Gas +Oil+Air	all	Kopejtko, Kocis 2013
32	Prestrike Fault recorders / Digital protection relay	Making analog record of currents and voltages in all three phases and signals like coil tripping. Then processing these records. Trigger condition for making the rcord: CB switching operation, short cut detection, overvoltage, overcurrent, …	Switching	General Diagnostic	Prestrike delays	In	Non	Con.	Commercial product available	HV+ MV	VCB+Gas +Oil+Air	all	Kopejtko, Kocis 2013
33	Number of operation	Recording number of operation either from SCADA system or operation counter.	Mechani-cal	Wear	WEAR_#op erations	In	Non	Con.	Standard practice in the field	HV+ MV	VCB+Gas +Oil+Air	all	
34	Trip Coil Analysis Case Studies	Three utility companies case studies of evaluating trip coil signatures and other circuit breaker parameters utilizing available circuit breaker analyzers	Control and Acces-sories	General Diagnostic	Timing of operation	In & Off	Min	Per.	Standard practice in the field	HV+ MV	VCB+Gas +Oil+Air	all	Larson 2009

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35	Mechanical Condition Re-cognition	New research method utilizing Automatic Dynamic Analysis Mechanical System (ADAMS) and Artificial Neural Networks (ANN) to model CB wear and predict failure	Mechani-cal	Wear	n/a	In	Non	Con.	R&D-Activity	MV	VCB	all	Rong 2005
36	PD measurement		Insulation	PD	PD-RF	In	Non	Con.	Tested in the field	MV	all	AIS	Kane2003
37	Daily Integrity Checks	Performing daily integrity check on DFRs to check that the data them is accurate and configuration is appropriate.	Switching	General Diagnostic	n/a	In	Non	Per.	Tested in the field	HV+ MV	n/a	n/a	Fecteau2005
38	Vibration analysis with wavelets	Use of wavelet analysis to characterize the vibration signature of and determine the health of the CB	Mechani-cal	General Diagnostic	Timing of operation	In	Non	Con.	Tested in the field	HV+ MV	n/a	n/a	Lee2002
39	Vibration analysis	An accelerometer is mounted inside the drive in order to record operation (O+C) vibration signatures which are compared to a reference (fingerprint)	Mechani-cal	General Diagnostic	Timing of operation	In	Min	Con.	Tested in the field	HV+ MV	VCB+Gas +Oil+Air	all	Hoidalen2005 Runde2005
40	Circuit breaker operating time	The circuit breaker opening time is accurately detected/measured through primary current analysis	Switching	General Diagnostic	Timing of operation	In	Non	Con.	Tested in the field	MV	n/a	all	Sheng2005 Li2005 Chan2005 Xiangjun2005
41	Comprehensive HV CB monitoring system	gas density (alarm/lockout thresholds, trends) travel curve analysis (op. time, speed, overtravel, rebound) electrical wear cumulation recharging time (spring/hydraulic pump)	Insulation	General Diagnostic	ISO-gas density	In	Min	Con.	Commercial product available	HV	Gas	n/a	

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42	distance-time (travel) character-istic	In order to discover hidden trouble in mechanical system, the distance-time characteristic and different Mechanical Characteristic parameters of CB should be pickedup and analyzed	Mechani-cal	Travel	Timing of operation	In	Min	Con.	R&D-Activity	HV+ MV	VCB+Gas +Oil+Air	all	
43	Trip Coil Profiling	The breaker trip coil current is measured and compared to a nominal baseline profile. The profile can be divided into several regimes that correspond to mechanical actions of the trip system.	Control and Acces-sories	Travel	TRAVEL-current profile	In	Min	both	Standard practice in the field	HV+ MV	VCB+Gas +Oil+Air	all	inproceedings Henderson 1996
44	PD measurement	Generic description of PD detection by means of TEV, ultrasonic, and capacitive sensors capture discharge magnitude, repetition rate, and differential time of flight. Results are interpreted based on manufacturer's database of PD fingerprints.	Insulation	PD	PD-TEV	In	Non	both	Commercial product available	HV+ MV	n/a	all	inproceedings Dennis2006
45	Temperature Monitoring	A method to locally monitor the internal temperature of medium voltage switchgear to minimize catastrophic failures. Permissable temperature levels are set for alarming and disconnection of the switchgear.	Current carrying	Temperatur e	Timing of operation	In	Non	Con.	Commercial product available	MV	VCB+Gas +Oil+Air	Solid-Ins.	Vlase2010
46	Dynamic contact resistance	A DRM method to measure the contact resistance during an opening operation at low speed.	Current carrying	Wear	WEAR-Re-sistance	Off	Non	Per.	Tested in the field	HV	Gas+Air blast	n/a	Landry2004

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47	Shock absorber test	The motion profile of a mounted motion transducer revieals the condition of the shock absorbers	Mechani-cal	Travel	TRAVEL-rotary (speed, acc,..)+ TRAVEL-linear (speed, acc,..)	Off	Min	both	Standard practice in the field	HV+ MV	VCB+Gas +Oil+Air	all	Levi2012
48	Contiuously monitor CB condition	Tutorial which defines the requirements for an online monitoring system and describes which circuit breaker parameters should be monitored. (I.e. contact travel, pressure, moisture, currents, voltages and travel)		General Diagnostic		In	Non	Con.	Tested in the field	HV	all	all	Landry1997
49	PD Detection on MV Switch-gears	A high frequency current sensor is installed around the conductor, where high frequency PD-current is passing through. The current is inducing a magnetic field within the ferromagnetic core of the sensor. The induced voltage is measured via a measuring burden, which is normally the input impedance of the PD-measuring instrument.	Insulation	PD	PD-RF	In	Non	both	Commercial product available	MV		all	Kornhuber2012
50	CD Condition with ARM & FPGA	A real-time monitor system for a variety of characteristic parameters of HVCB, based on FPGA and ARM		General Diagnostic	n/a	In	Non	both	Theoretical Concept	HV	Gas	GIS	Huang2009
51	Breaker Timing using RF impulse	Interpole switching time is measured by detecting the RF impulses generated by arc duting the breaker operation	Switching	General Diagnostic	TRAVEL-time	In	Non	both	R&D-Activity	HV	VCB+Gas +Oil+Air	all	Moore2004

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52	Attached magnetron gauge	A miniature presure gauge attached after production allows pn-line pressure meas. over a limited pressure range; requires special type of VI, thus not generally applicable; however the reliability of the gauge itself is not investigated yet	Insulation	Insulation Medium	ISO-vacuum quality	In	Non	both	R&D-Activity	MV	VCB	all	Mao2007
53	Mobile Magnetron	based on stationary application of magnetron discharge for pressure determination with a flex-coil	Insulation	Insulation Medium	ISO-vacuum quality	Off	Non	Per.	Prototype available	MV	VCB	AIS	Ledbetter2012
54	CB Monitoring System	Multiple mechanical measurements system to predict CB health (position signals, time between operations, operation counter, contact travel time, contact quality, contact bouncing, spring charging time)	Mechani-cal	Travel	TRAVEL-profiler test	In	Stron gly	Con.	Prototype available	MV	all	all	Saeli2012
55	CB Monitoring System	Motor current, linear/angular position measurements system to predict CB health	Mechani-cal	Travel	TRAVEL-rotary (speed, acc,..)	In	Stron gly	Con.	R&D-Activity	MV	VCB	all	Lin2011
56	New CB Mechanism	Simple motor drive mechanism with multiple condition monitoring (drive motor angle, stored electrical energy level, motor current)	Mechani-cal	Travel	TRAVEL-rotary (speed, acc,..)	In	Stron gly	Con.	R&D-Activity	HV	Gas	n/a	Bosma2001
57	MCCB Monitoring	Measurement of DC motor current with tangential torque derived to predict issues with operating mechanism (low voltage application)	Mechani-cal	Travel	AUX-motor current	In	Min	Con.	R&D-Activity	MV	Airblast	AIS	Li2011
58	CB Monitoring System	Multiple measurements (opening/closing time, motor current, non-simultaneity) reported via SCADA; specifically minimally intrusive	Mechani-cal	Travel	AUX-motor current	In	Min	Con.	R&D-Activity	HV	Gas	n/a	Kayano2004

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59	CB Monitoring System	Monitoring of dynamic contact travel and current in release coils	Mechani-cal	Travel	TRAVEL-linear (speed, acc,..)	In	Min	Con.	Prototype available	MV	VCB	all	Shi2002
60	DC Solenoid Monitoring	Measurement of DC solenoid closing current to detect abnormalities	Mechani-cal	AUX	AUX-coil current	In	Min	Per.	Prototype available	HV+ MV	VCB+Gas +Oil+Air	all	Sugimoto2002
61	Linear Position Transducer	Dynamic contact travel measurement using Doble TR3171	Mechani-cal	Travel	TRAVEL-linear (speed, acc,..)	In	Min	Per.	Mature product available	HV+ MV	VCB+Gas +Oil+Air	all	Morgan2014
62	Vibration analysis	An accelerometer mounted on the breaker mechanism to analyze the vibration during the close, open or charging operation	Mechani-cal	General Diagnostic	Timing of operation	In	Non	Per.	Tested in the field	HV+ MV	VCB+Gas +Oil+Air	all	Cadick2014_1
63	Breaker Timing using Relay	First Trip time is measured by programming the protective relay	Mechani-cal	General Diagnostic	Timing of operation	In	Non	Per.	Tested in the field	HV	VCB+Gas +Oil+Air	all	Desai2012
64	Circuit Breaker Sentinel (CBS) System	Online monitoring of multiple parameters of the HV SF_6 Circuit Breakers	Mechani-cal	General Diagnostic	TRAVEL-profiler test	In	Non	Con.	Tested in the field	HV	Gas	GIS	Poltl2011
65	CB status	Measurement of coil current, contact travel and overtravel, derivation of contact travel velocity. Correlation of open/close signals to current in the main circuit. This paper is focused on the computer that collects the monitoring information.	Mechani-cal	AUX	AUX-coil current	In	Min	Per.	R&D-Activity	HV	Gas	n/a	Chunguang 2009
66	CB status	Multiple measurements (opening/closing time, coil current, contact travel) in an integrated condition monitoring and diagnosis system. Not too much detail on the mechanical techniques.	Mechani-cal	AUX	AUX-coil current	In	Min	Per.	R&D-Activity	MV	VCB	GIS	Jang2011
67	CB status	Measurement of capacitor voltage (stored energy state)	Mechani-cal	AUX	AUX-spring charge	In	Min	Con.	Standard practice in the field	MV	VCB	GIS	JST2007 (Japanese language)

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68	Vibration signatures	Preliminary Investigation for Application of MEMS Acceleration Sensor to SF_6 Gas Circuit Breaker	Mechani-cal	Travel	TRAVEL-linear (speed, acc,..)	In	Non	both	Mature product available	HV+ MV	all	all	Hisatoshi2008
69	Vibration signatures	An Improved Vibration Analysis Algorithm as a Diagnostic Tool for Detecting Mechanical Anomalies on Power Circuit Breakers	Mechani-cal	Travel	TRAVEL-linear (speed, acc,..)	In	Non	both	Mature product available	HV+ MV	all	all	Landry2008
70	Vibration signatures	Research on Acceleration Phenomena with Test Equipment of Simulating Puffer type Gas Circuit Breaker	Mechani-cal	Travel	TRAVEL-linear (speed, acc,..)	In	Non	both	R&D-Activity	HV+ MV	all	all	Ikeda2009
71	Vibration signatures	Failure Mechanism Analysis of Quartz Accelerometer under Vibration Condition	Mechani-cal	Travel	TRAVEL-linear (speed, acc,..)	In	Non	both	R&D-Activity	HV+ MV	all	all	Ran2011
72	Vibration signatures	A noninvasive diagnostic instrument for power circuit breaker	Mechani-cal	Travel	TRAVEL-linear (speed, acc,..)	In	Non	both	Mature product available	HV+ MV	all	all	Naidu1991
73	Vibration signatures	Vibration Analysis for Diagnostic Testing of Circuit Breaker	Mechani-cal	Travel	TRAVEL-time	In	Non	Con.	R&D-Activity	HV+ MV	all	all	Runde1996
74	Vibration signatures	Continuous Monitoring of Circuit Breakers Using Vibration Analysis	Mechani-cal	Travel	TRAVEL-time	In	Non	Con.	Tested in the field	HV+ MV	n/a	n/a	Hoidalen2005
75	Vibration signatures	The Detection of the Closing Moments of a Vacuum Circuit Breaker by Vibration Analysis	Mechani-cal	Travel	TRAVEL-rotary (speed, acc,..)	In	Non	both	R&D-Activity	MV	all	all	Meng2006

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76	Vibration signatures	Mechanical Defect Detection of SF_6 High Voltage Circuit Breaker Using wavelet Based Vibration Signal Analysis	Mechani-cal	Travel	WEAR_#operations	In	Non	both	R&D-Activity	HV	n/a	n/a	Charbkeaw 2008
77	Vibration signatures	Use Vibration Monitoring to Identify Circuit Breakers for Condition Assessment	Mechani-cal	Travel	TRAVEL-time	In	Non	both	R&D-Activity	MV	VCB	AIS	Wang2009
78	Vibration signatures	On-line Monitoring System for Switching Synchronization of Ultra-high Voltage Circuit Breaker in GIS	Mechani-cal	Travel	TRAVEL-time	In	Non	both	R&D-Activity	HV		n/a	D.Li2011
79	PD measurement	PD pulse acquisition,measurement of apparent charge,evaluation of magnitude, repetition rate,frequency and phase angle, detected by inductive sensor (HFCT)	Insulation	PD	PD-electrical	In	Non	Per.	Standard practice in the field	HV		GIS	IEEE 2012
80	PD measurement	PD pulse acquisition,measurement of apparent charge,evaluation of magnitude, repetition rate,frequency and phase angle, detected by shield electrodes embedded in the solid insulator of bushings used as capacitive sensors	Insulation	PD	PD-electrical	In	Min	Per.	Tested in the field	MV		GIS	IEEE 2012
81	SF_6 gas density & moisture measure-ment	[Muyi2010] A microprocessor based online monitoring device is introduced. The device monitors "temperature", insulation (SF_6 gas moisture and density), electric and mechanical parameters of HVCB. An actual installation at a 6.6kV substation is presented.	Insulation	Insulation Medium	ISO-gas density	In	Min	Con.	Mature product available	HV	Gas		Li_Muyi2010
82	PD measurement	[Deng2011] A fundamental research of PD detection methods for Vaccum Interrupters (VI) is presented. A capacitive coupling sensor is used. The output signals of the sensor are recorded by an oscilloscope and the profiles are investigated.	Insulation	PD	PD-electrical	In	Min	Con.	R&D-Activity	MV	VCB	AIS	XinDeng2011

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83	SF_6 quality measurements	various sensors and measurement methods such as "dew point mirror", "aluminum oxide sensor" and "decomposition gas detector tube" are present in Cigre Brochure.	Insulation	Insulation Medium	ISO-by-products	In	Non	both	Mature product available	HV+ MV	Gas	AIS+GIS	Cigre TB 567
84	SF_6 quantity measurements	Sensors and mesurement methods for SF_6 gas density moitoring such as "tuning fork" and "temperature compensated gauge" are present in Cigre Brochure	Insulation	Insulation Medium	ISO-gas density	In	Non	both	Mature product available	HV+ MV	Gas	AIS+GIS	Cigre TB 567
85	Vacuum quality monitoring	Magnetrons to measure vacuum level of Vacuum interrupters at field / lab are introduced.	Insulation	Insulation Medium	ISO-vacuum quality	Off	Non	Per.	Mature product available	MV	VCB	AIS	Doble2014
86	Oil quality analysis	Lab programs for oil analysis by Doble and TKH2b are presented.	Insulation	Insulation Medium	ISO-DGA	Off	Non	Per.	Mature product available	HV	Oil		Doble& TKH2b check sheets
87	PD measurement	Unconventional partial discharge measurement techniques for MV switchgears using capacitive voltage denectors (VDS), high-frequency CT (HFCT) and transient earth voltage sensors (TEV) are evaluated their advantages and disadvantages.	Insulation	PD	PD-electrical	In	Non	both	Mature product available	MV	Gas	GIS	Bernd2014
88	PD, X-ray, Moisture content, IR and UV	Condition monitoring state of the art of several techniques used in the field in the CN SGCC and CSG	Current carrying	General Diagnostic	n/a	In	Non	both	Standard practice in the field	HV+ MV	all	all	
89	Electric field measurement	An electro-optic sensor for non-invasive electric field measurements. The technique is not sensible to magntic field and temperature variations.	Control and Acces-sories	General Diagnostic	n/a	In	Non	Per.	Prototype available	HV+ MV	all	all	
90	Temperature Measurement	Temperature measurement based on detection of Infrared radiation.	Current carrying	Temperature	n/a	In	Min	Con.	Commercial product available	HV	Gas	GIS	
91	Temperature Measure-ment	Temperature monitoring of GIS contacts based on IR technology.	Current carrying	Temperature	n/a	In	Min	Con.	Theoretical Concept	HV+ MV	Gas	GIS	

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92	Ablation measure-ment	Contact ablation measurements of arcing contacts.	Control and Acces-sories	Wear	n/a	In	Min	Con.	Commercial product available	HV+ MV	Gas	AIS+GIS	
93	End of life determi-nation	Service raw data used for diagnostic and prognostic of the circuit breaker.	Control and Acces-sories	Wear	WEAR_#operations	In	Non	both	Commercial product available	HV+ MV	all	all	
94	Density monitoring of high voltage SF_6 CB's.	Density monitoring comparison using different transducers and sampling rates.	Control and Acces-sories	Insulation Medium	ISO-gas density	In & Off	Non	both	Commercial product available	HV+ MV	Gas	AIS+GIS	
95	Temperature Monitoring	Passive, wireless and battery-less measurement of temperature.	Current carrying	Temperature	n/a	In	Non	both	Commercial product available	HV+ MV	Gas	AIS+GIS	
96	Radiographic inspection saves costs and downtime and enables better maintenance planning	The use of radiography (X-Ray) technology, in combination with other established non-intrusive circuit breaker testing techniques, to determine the health of the equipment. This will become the basis for developing the best maintenance plan.	Mechani-cal	Wear	n/a	Off	Non	Per.	Mature product available	HV+ MV	Gas	AIS+GIS	Michaelson 2012
97	Failure contri-butors of MV electrical equipment and condition assessment program develop-ment	Analysis of GIS and circuit breaker (138kV and above) failure modes to select the appropriate on-line diagnostic tools to implement a condition based maintenance program.	Mechani-cal	Wear	n/a	In	Non	Con.	Mature product available	HV+ MV	VCB+Gas +Oil+Air	AIS	Paoletti and Maier 2002
98	Dynamic Resistance Measure-ment							Per.	Tested in the field	MV	Gas	GIS	
99	Dynamic Resistance Measurement method applying high DC current							Per.	Prototype available	HV	Gas	GIS	

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100	Condition Assess-ment of EHV class Circuit Breakers using Dynamic Contact Re-sistance Measure-ment Technique							Per.	Tested in the field	HV	Gas	GIS	
101	Analysis of modern high voltage circuit breaker failure during shunt reactor switching operations and corrective measures	Detecting fast transients via RF / capacitive coupling antennas : restrikes, inrush currents : passive + active antennas are positionned at ground level to capture signals during switchings.	Switching	General Diagnostic	Restrikes Re-ignitions	In	Non	Con.	Tested in the field	HV	Gas	n/a	Lopez-Roldan, Blundell, Wing, Birtwhistle, Ramli, Tang 2007
102	Investigation of circuit breaker switching transients for shunt reactors and shunt capacitors	Thesis RF method as above. Open + Close operations, many screenshots	Switching	General Diagnostic	Restrikes Re-ignitions	In	Non	Con.	Tested in the field	HV	Gas	n/a	Ramli 2008
103	Examples of condition based maintenance in distribution systems	Use of Digital fault recorder datas. Detection of reignitions, current spikes…	Switching	General Diagnostic	Restrikes Re-ignitions	In	Non	Con.	Tested in the field	MV	n/a	n/a	El-Hadidy, Helmi 2011
104	Automatic collection and evaluation of monitored HV equipment service conditions	Datas from digital fault recorders (DFR) are collected and analyzed in order to detect various malfunction of HV switchgear.	Switching	General Diagnostic	Restrikes Re-ignitions	In	Non	Con.	Tested in the field	HV	n/a	n/a	Kopejtko, Kocis 2007
105	New applications for Rogowski coils design in the electrical industry	Alternative to RF method to detect fast transients	Switching	Insulation Medium	Restrikes Re-ignitions	In	Min	Con.	R&D-Activity	HV	Gas	n/a	Dupraz, Fanget, Grieshaber, Montillet 2007

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106	Device for detecting and locating electric discharges in fluid-insulated electrical equipment	Patent US2010259275A1. In relation with above mentionned paper	Insulation	Insulation Medium	Restrikes Re-ignitions	In	Min	Con.	R&D-Activity	HV	Gas	n/a	Grieshaber, Fanget 2010
107	Method for discrimi-nating between an internal arc and a circuit breaking arc in a medium or high voltage circuit breaker	Patent US6236548B1	Switching	Insulation Medium	ISO-pressure	In	Min	Con.	R&D-Activity	HV+ MV	Gas	GIS	Marmonier 2001
108	A development and application of circuit breakers diagnostic and monitoring	travel curve analysis (op. time, speed, overtravel, rebound) electrical wear cumulation recharging time (spring/hydraulic pump)	Switching	Travel	TRAVEL-rotary (speed, acc,..)	In	Min	Con.	Commercial product available	HV	Gas	n/a	Dewulf, Jung, Dupraz, Montillet 2001
109	Online monitoring and fault diagnostics of mechanical conditions of high voltage dis-connector	Travel curve and motor current records of disconnectors are analyzed by likelihood method.	Switching	Travel	AUX-motor current	In	Min	Con.	Tested in the field	HV	all	n/a	Lin, Xiong, Fu 2011
110	Data mining of online diagnosed waveforms for probabilistic consition assess-ment of circuit breakers	Classification and probabilistic approach for measurement. Help for decision makin (Emergency / Alarm / normal)	Switching	General Diagnostic	AUX-coil current	In	Non	Con.	R&D-Activity	HV+ MV	n/a	n/a	Razi-Kazemi, Vakilian, Niayesh, Lehtonen, 2014