OVERVIEW OF NON INTRUSIVE METHODS FOR SWITCHGEAR CONDITION ASSESSMENT (CIGRE/CIRED JWG A3.32)

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ABSTRACT

This paper presents an overview of Non-Intrusive Condition Assessment that can be applied on HV and MV circuit switchgear. Many emerging non-intrusive techniques are reported in the literature, most of them allowing in service evaluation. The CIGRE/CIRED Joint Working Group A3.32 reviewed the current and future trends of non-intrusive, especially in service, diagnostic methods completing the work on Condition Assessment of Switchgears. This can be valuable information for anyone who is going to apply or improve Condition Assessment Methods to Switchgears.

INTRODUCTION

With plummeting prices for renewables and energy storage, proliferation of distributed energy resources, and grid modernization with the subsequent two-way power flow, we witnessed the rapid change in the power grid in the last decade. Switchgear design is following suit, evolving from a manually operated device to an interconnected "smart" unit with embedded sensors, digital protection and control devices.

And while switchgear designs are getting more "smart" and more complex, requirements for the electrical grid are becoming more stringent; including reduction of power outages, higher safety, health and environmental requirements, and improved power quality. Such requirements influence switchgear specifications, design and – of course - maintenance.

To reduce the maintenance costs of switchgear equipment, there is a general trend in the utilities to move from time-based maintenance to condition and risk based maintenance. Consequently, the need for less intrusive methods is increasing.

For the above reasons, the CIGRÉ/CIRED Joint Working Group (JWG) A3.32 was formed to analyse the state of the art of non-intrusive methods and their field experience applied to circuit breakers, reclosers and other switchgear in both transmission and distribution grids.

32 members from 15 countries have been working on this topic for 4 years and the work resulted in a CIGRE/CIRED technical brochure that was published in August 2018 [1]. The authors identified 55 non-intrusive diagnostic methods and list over 200 references about them. In addition, an international utility survey has been conducted about the methods used for condition monitoring. Its results give a qualitative insight on the current switchgear diagnostic practices within utilities. Lastly, some useful tools for technical and economic analysis of the diagnostic methods are presented.

WHY PERFORM CONDITION ASSESSMENT?

The goal of Non-Intrusive Condition Assessment Methods (NICAM) is to reduce the overall costs of asset management. These can be justified if the net benefit results are positive from its application. Several techniques can be used to assess these benefits and from different perspectives, all the methods compare three main cost elements:

1. Investment on NICAM
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.

Independently from the specific diagnostic technique or technology, the basic concept is applying NICAM to assess the switchgear condition over time, reducing costs connected to maintenance and operation or to major failure probability of the asset, namely:
- Reduction of outage cost
- Reduction of repair cost

A process to come to a quantitative evaluation can follow these steps:
- Define the failure probability as a function of asset age.
- Assign a cost of failure
- Calculate the economic benefit for every year (i) due to the reduction of failure probability coming from

condition assessment.

The usefulness **U** of the applied method is how effective a failure can be prevented reducing the associated failure probability. Its estimation 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 asset assessment reducing the probability of major failures.
- When the failure risk probability decreases the risk value is reduced.

A graphical representation is given in **Figure 1.** The grey points represent the failure risk probability distribution and the orange and blue lines are the 90th and 10th percentile respectively.

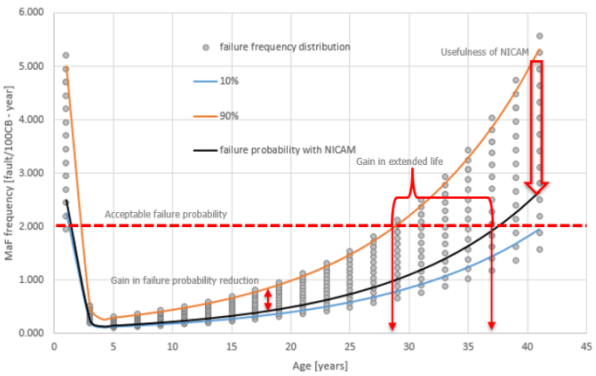

Figure 1: *Principle representation of frequency of major failure and failure probability curves as a function of the age of asset*

The failure frequency distribution as a function of asset age has to be defined according to experience. The acceptable failure probability (dashed red line) is defined by the asset manager. Applying NICAM the failure probability decreases. The total economic benefit along the whole asset life of (n) years can be evaluated taking into account the contribution E_i of every year (i) actualized to the year 0 with a given interest rate (r).

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

Where n is the number of years which is considered for the investement. The calculated amount E_{cum} has to be compared with the investment needed to apply NICAM.

Reducing the failure probability allows an extension of the asset life within the set asset reliability level. In **Figure 1** the asset renewal to ensure the wished failure probability without NICAM is planned after approximately 28 years. Applying NICAM the same failure risk probability (red dashed line) can be guaranteed for more than 36 years of life with a benefit of 8 years of renewal deferral.

Condition assessment leads to higher asset reliability and offers economic benefits in term of failure risk reduction as well as asset life extension. Besides the condition indicators to be assessed and the asset typical failure modes, the Usefulness of the selected NICAM is a key factor and the major link between the technical benefits of a method and its economic viability.

WHAT ARE THE CURRENT PRACTICES?

To get a better understanding of current condition assessment practices, A3.32 JWG conducted a survey among 49 utilities from 18 different countries. **Figure 2** shows the results for in-service and off-service methods for switchgear 38 kV and below.

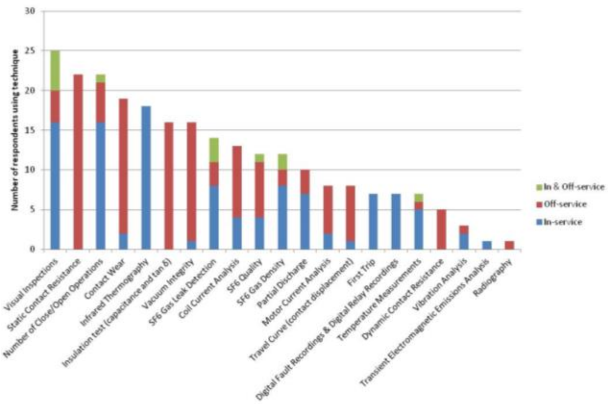

Figure 2*: List of switchgear non-intrusive condition methods, identified through the international utility survey.*

The most used in-service methods are those that are easy to perform and interpret like visual inspection, number of close/open operations and infrared temperature measurements. The newer techniques like vibration and radiography are used infrequently. They are reported to be either difficult to use or difficult to analyse.

These results indicate that utilities are more likely to deploy condition assessment methods that are easy to use and don't require an expert system to analyse.

In addition, utilities answered favourably on the question of cost benefit using non-intrusive condition assessment (**Figure 3**). Therefore, it can be expected that NICAM will be used more in the future in order to be able to better predict the end of life.

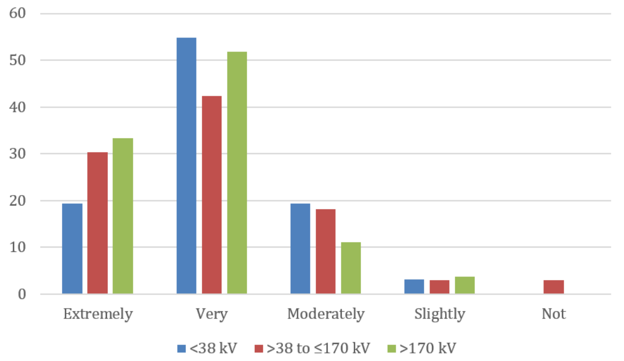

Figure 3: *Importance of the cost advantage of using non-intrusive diagnostic techniques*

OVERVIEW OF THE METHODS:

In this paper, a few non-intrusive condition assessment methods are presented that are relevant to MV switchgear. For the whole list of methods, please refer to [1]. Short summary at the end of each method in → *italic* indicates whether it is periodic or continuous measurement and what level of maturity it has for actual application.

Vacuum Condition

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 [2]. The performance of the VI is connected to the vacuum level, though not simply proportional to the pressure.

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 [3,4]. 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. 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. 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. Uncertainties can arise during the mobile magnetron test, especially from the Getter-Ion Effect. It limits the repeatability of the magnetron measurement. Any switching operation has an effect on the residual gas composition and the total pressure inside the VI and hence the measuring result. Thus the analysis of the internal pressure measurement must be done by an expert system.

→ *Periodic measurement, prototypes have been tested*

Dielectric vacuum testing can also be done by applying a high voltage across the open vacuum interrupter contacts [2]. These techniques are using an AC or DC voltage of ~80% of the rated voltage at power frequency. The DC method is generally used in the so-called "vacuum checkers" that are commercially available. Both techniques require the switchgear to be disconnected. The equipment for the DC voltage test is often very compact. The DC test can misinterpret field emission current from the contacts at a high vacuum level.

→ *Periodic measurement, standard practice in the field*

Gauges directly incorporating into the vacuum interrupter can monitor the pressure directly. The **cold cathode gauge** requires a magnetic field, similar to the magnetron, to increase the chance of a collision with a molecule and a potential difference between the two terminals. The current drawn between the electrodes is then proportional to the pressure. The **spinning rotor gauge** uses a small metal ball that is magnetically levitated and driven to rotate. 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 proportional to the pressure.

Both types of gauges need to be built-in to the VI from the start. The next difficulty in the application of them is making the electrical connections to the gauges. As 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.

→ *Continuous measurement, prototypes available*

Atmospheric pressure produces a significant closing force on the moving terminal of the VI's. 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, resulting in a change of the mechanical behaviour of the VI. This is widely used to test VI's during out-of-service maintenance.

The main method for **mechanical pressure monitoring** attaches an additional moving part to the VI using a bellows or similar (**Figure 4**), and the complete loss of vacuum then results in the motion of this component [5]. This technique would only provide a pass/fail measurement of whether the VI was up-to-air or not.

The application of an AC voltage below the breakdown voltage can generate micro-discharges, which transfer some pico-coulombs of charge, and can be detected with specialized PD measurement equipment. In vacuum, various features of the partial discharge signal change with the internal pressure of the VI [6]. These systems could detect vacuum levels in the mid-range of pressure only. The performance in the up-to-air region is unknown.

Acquiring a PD signal requires a voltage difference in the VI over the open contacts, resulting in a periodic measurement of the pressure. It could be dependent on the design of the VI. 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.
→ *Continuous measurement, prototypes have been tested*

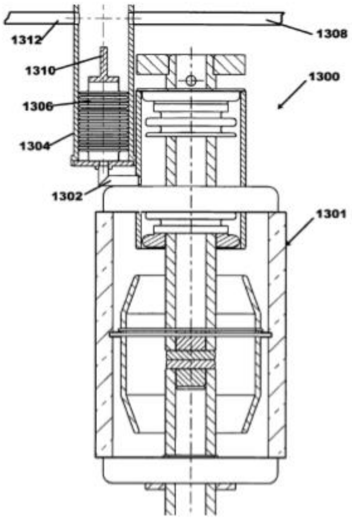

Figure 4: *Pressure monitoring via an additional bellows (1306) attached to the VI. A tube connects the additional bellows to the VI (1302), and the movement of part (1310) during loss of vacuum breaks the light path between (1308) and (1312) [5].*

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. Vibration signals can be measured in non-intrusive ways which allow online monitoring.

A non-invasive **direct ablation measurement method** based on vibration signal analysis was developed [7] for application on high-voltage circuit breakers (**Figure 5**).

The delay between the opening of the main contact and the opening of the arcing contact is calculated. Then it is possible to monitor how the arcing contact gets shorter due to ablation. This method requires that all accelerometers are attached uniformly, and they must be placed in the arc extinguishing chamber to eliminate the vibration signal produced by the drive mechanism. The method is not suited for porcelain pole breakers, whereas it works for tank type breakers.
→ *Periodic measurement, R&D activities*

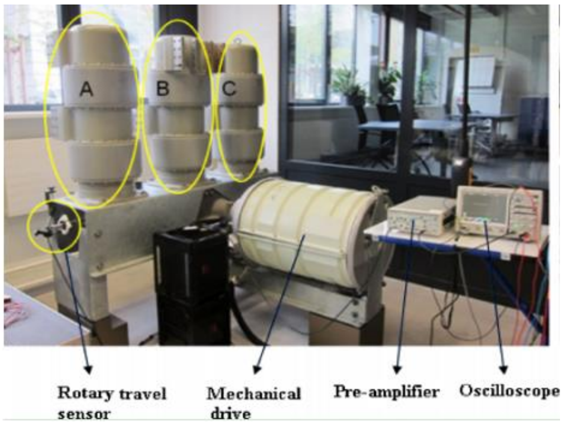

Figure 5: *Measuring setup for 3 pole circuit breakers [7]*

A **dynamic time** wrapping algorithm [8] for analysing the vibration pattern has been developed and can be used as a diagnostic tool for detecting mechanical anomalies of circuit breakers. See vibration patterns in (**Figure 6**). [8]
→ *Periodic measurement, mature product available*

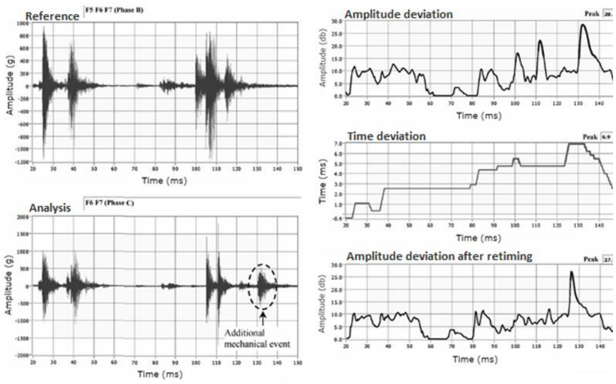

Figure 6: *Graphs of the vibration analysis on a circuit breaker*

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. 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. 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 necessary to have a PD expert.

The **UHF method** was first developed in the late 80's for use in HV GIS and is currently used in MTS (Mixed Technology Switchgear) and in power transformers and

MV equipment.

PD appears as high frequency current pulses. The fast rise-time pulses provide a high frequency electromagnetic transient propagating inside the enclosure. They can be detected by antennas internally and externally mounted.
→ *Continuous measurement, standard practice*

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**. Therefore, this frequency range is used for measuring PD in cables and cable joints and less common for GIS switchgear.
→ *Continuous measurement, commercial products available*

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 external TEV sensor. [9] This method is predominately used for indoor metal enclosed MV switchgear and less common for GIS.
→ *Continuous measurement, standard practice*
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.
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 acoustic waves are detected and converted into electric signals by various sensors.
→ *Continuous measurement, commercial products available*

History of operations and I2t

I^2T represents the **energy during switching** (arcing) and goes in line with physical wear of contacts. For simplicity the exponent 2 is chosen as typical average value. The duration of each arc, t, is difficult to measure using typical measurement and protection equipment at the substations. Therefore it is assumed to be constant, although it varies. Sometimes only the fault interruptions are counted and the total I^2T corresponding to the end of life is uncertain; there is need for a margin.

A further simplification consists in **counting only the operations**. The protection relays count the interruptions due to faults whereas the circuit breakers have counters that record all operations. However, they can be mechanical and only available on site.
→ *Continuous measurement, standard practice*

CONCLUSION

This paper provides an overview of the Non-Intrusive Switchgear Condition Assessment methods and it is based on recently published CIGRE/CIRED technical brochure [1]. It has 3 sections. First, it answers the question why it is important to do the Condition Assessment and provides the means to calculate its economical benefit. Second, it provides a summary of current utility practices that were gathered through the international survey. The results indicate that utilities are going towards implementing less intrusive and easier to analyse methods. Lastly, the paper provides an overview of a few non-intrusive methods, relevant to MV switchgear.

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