ECONOMICAL AND PRACTICABLE CONDITION ASSESSMENT OF MV- AND LV-DISTRIBUTION GRIDS

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ABSTRACT

This paper describes a procedure of condition assessment for distribution grids which is applicable in an economical, non-intrusive and practical way. The assessment procedure is based on periodic visual inspections. It is additionally supplemented by suitable and simple measurement methods which can be used without any disconnection of the components and thus without much additional effort during an inspection. Therefore suitable non-intrusive measurement methods for medium voltage substations and switchgears as well as low voltage distribution cabinets will be presented in relation to an integrated condition assessment of distribution grids. But significance of these non-intrusive measurement methods is limited. Using the example of acoustic partial discharge detection measurement uncertainties will be determined by intensive laboratory tests and numerous field tests realized with several German distribution system operators. These values will be combined with condition information of visual inspections by using theory of evidence to express the uncertainty. Since measurements and visual inspections detect different kinds of deficiencies of electrical equipment, a combination of both is crucial to achieve a high significance of condition assessment as shown in this paper.

INTRODUCTION

German distribution system operators (DSOs) are continuously forced by the regulator to fulfil efficiency enhancements of their electrical distribution grids. Therefore the distribution system operators use optimized maintenance and replacement strategies for the grids like reliability centered maintenance (RCM) or risk based maintenance to reduce operational and capital expenditures [1]. The most objective and realistic condition assessment of various electrical components is the basis of all optimized maintenance strategies in asset management. Only if the actual technical asset condition is known, maintenance and replacement measures can be initiated specifically. Limited financial resources are allocated to the "right" components – those having the worst condition. DSOs mainly use periodic visual inspections in an interval between one year and four years in order to determine the actual technical asset condition. Results of visual inspections for condition assessment and several countermeasures to make them more reliable are already presented in [2]. But it has also been shown that a purely visual inspection of electrical components is sometimes limited, especially for electrical equipment, because partial discharges or thermographic hot spots cannot be detected visually. As a result uncertainty of visual condition assessment for electrical equipment is at a high level and should be considered in decision-making process. In order to achieve a well-founded and comprehensible basis for condition assessment measurement methods should be supplemented.

CONDITION ASSESSMENT FOR MEDIUM AND LOW-VOLTAGE COMPONENTS

For components in high and extra-high voltage level condition assessment is based on various measurement methods that detail actual condition of components. However, the use of these measurement methods involves considerable effort, which is justified because components in these voltage levels are almost unique and have a high single value. In contrast to that the single value of medium- (MV) and low-voltage (LV)-components is very low, but their number in distribution grids is very high and they are almost similar. As a result condition assessment of MV- and LV-components has to be cost-effective which means that expensive measurement methods cannot be used. Justified effort for condition assessment depends on the voltage level and is shown in figure 1.

Figure 1: Justified assessment depending on voltage level

As already noted above, the use of measurement methods is highly recommended for a well-founded and comprehensible condition assessment especially for electrical components. Related to the measurement methods for MV and LV components, different potential measurement devices have been selected which can be used without any disconnection of the components during an inspection. Therefore they were tested in the high voltage laboratory of Wuppertal University using realistic MV components, e.g. a 40 years old MV substation. Hence, the applicability and influencing factors on measurement results were determined.

The following measurement methods have proven to be suitable and effective for generating valuable benefit for condition assessment of air-insulated MV and LV components:

- Acoustic detection of partial discharges
- Detection of transient earth voltages (TEV)
- Earth-loop testing
- Thermal imaging

Conventional partial discharge measurement

Partial discharge (PD) measurement is only suitable for condition assessment of MV components (or components of higher voltage level) because PD will not appear at LV components due to Paschen's law. PD will be divided into three categories: corona, surface and internal PD. PD only partially bridges the distance between two electrodes or an electrode and an isolator. Long-time appearance of PD may lead to disruptive discharges, as isolating materials are eroded by PD [3].

Referring to IEC 60270 (conventional PD measurement) PD can be measured using a coupling capacitor being parallel-connected to the components of interest for PD measurement. Using conventional PD measurement components have to be taken out of service to install the coupling capacitor. Additionally, a discharge free power supply is needed for the measurement.

PD can be interpreted by evaluation of their pattern and magnitude which is specified in pico-coulombs. However, this method does not provide any indication of the location of it's source. Referring to Figure 1 the effort to measure PD by using conventional measurement methods as a part of an inspection in MV level exceeds by far the justified values. Even components cannot be turned out of service for an inspection, because of outage time regarding all customers.

Consequently, measurement methods which are applicable to MV components in the field without any switching operation have to be used. Regarding PD measurements these are acoustic PD detection to measure corona as well as surface discharges and detection of transient earth voltages to detect internal PDs.

Acoustic partial discharge detection

Corona and surface discharges emit ultrasonic waves. These waves are specific for these discharges and propagate as travelling waves spreading out from source. Detection of ultrasonic waves is practically possible by using microphones with a high sensitivity in ultrasonic frequency range. Distracting ambient noise is filtered as only waves in ultrasonic frequency range are detectable. Determining the location of PD becomes possible by using directional microphones or ultrasonic solid-borne sensors for acoustic PD. This constitutes the main benefit of this detection method in contrast to conventional PD measurement [4].

A schematic illustration of the corresponding operating principle is shown in figure 2. The top figure 2 shows occurrence of PD at needle to plate arrangement. Resultant ultrasonic waves propagate in air and can be detected by directional microphone consisting of handle, parabolic reflector and ultrasonic microphone. If components are encapsulated, a solid-born ultrasonic sensor will be used instead of a directional microphone. The bottom figure 2 shows the detection principle, where solid-borne sensor is adapted to enclosure. Ultrasonic waves of PD will travel inside the enclosure and for traveling critical angle has to be exceeded. Additionally, different velocities of propagation have to be considered. Highest detected PD level may occur at fastest traveling path instead of shortest path. That link has to be taken into consideration to interpret measured values.

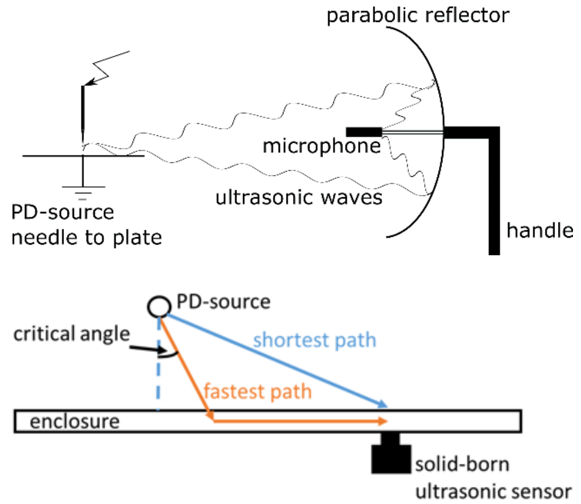

Figure 2: Operating principle of directional microphones (top) and solid-born ultrasonic sensor (bottom) [cf. 5]

The application of acoustic sensors without any disconnection of components is an important advantage. Thus, analysing air-insulataed MV components with regard to PD is possible during an inspection. However, it is not possible to match acoustic PD measurement and conventional measurement as stated in IEC 60270, which is the main restriction for all unconventional detection methods of PD. Magnitude of PD is analysed by acoustic methods and depends on various factors such as distance to the source of the PD [6] or applied sensors. Besides the displayed magnitudes - in decibel micro volts ($dB_{\mu V}$) - the devices often support an acoustic output for headphones. By using headphones the repetition rate of PD can be recognized and differentiation between PD and disturbances included in ultrasonic frequency spectrum becomes possible.

If measurement distance is considered and adjusted using formula in [6], laboratory tests will show that increasing PD lead to higher acoustic magnitudes. The median of 25 different measurement arrangements for various voltages - with regard to proportion of disruptive voltages - for needle to plate arrangement is presented in Figure 3. Resultant curve of acoustic PD detection for needle to plate arrangement resembles theoretical characteristics of this arrangement using conventional PD measurement. PD level will increase until the inception voltage is reached and will stay at approximately 28 % of disruption voltage. At approximately 65 % of disruptive discharge value of acoustic PD detection increases again up to a level of 68 $dB_{\mu V}$, that represents acoustic value at disruptive discharge.

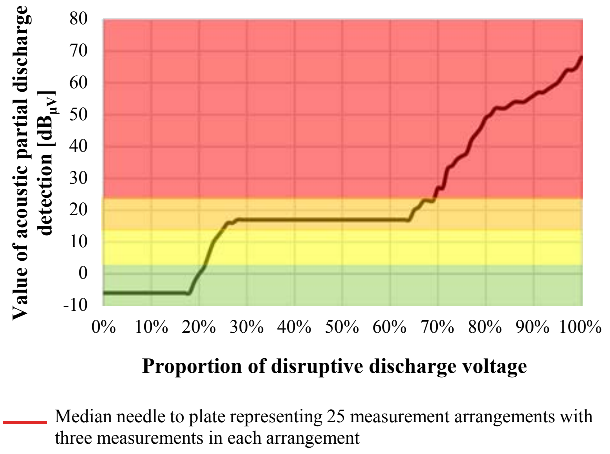

Figure 3: Dependence of measurement value to proportion of disruptive voltage for needle to plate arrangement

In figure 3 resultant maintenance requirements were defined accordingly:

- Green area: “no deficiency detectable”
- Yellow area: “long-term maintenance required”
- Orange area: “short-term maintenance required”
- Red area: “immediate maintenance required”

Thermal imaging

Infrared radiation is emitted by objects with temperatures above T = -273.15 °C and can be detected with thermal imaging devices. Emission of electromagnetic radiation depends on material properties and specific emission coefficients (ε_r) for different materials. Even factors for transmission (τ) and reflection (φ) have to be considered for exact thermographic analyses of components [7].

Due to losses on contacts or connections, electrical components will heat up during operation. Without any defect temperature of contacts and components complies with critical values that result from material specific properties. If a contact of a component is defective or load exceeds limits, components will heat up extremely and may be destroyed [7]. For detection of MV and LV components temperature thermal imaging cameras are used because of an adequate balance between benefits and effort. Correct factors for emission, reflection and transmission only have to be considered to determine absolute temperatures. While absolute temperatures of components are important but not crucial at all [6], differences in temperature of similar components are more meaningful. Components of the same panel are normally loaded equal and exhibit a uniform temperature distribution. Consequently, they should have nearly the same absolute temperature. Due to these facts they are in the focus of interest for analysis. If there is a looming defect, differences in temperature distribution will occur while the absolute temperature does not exceed critical values. Regarding differences in temperature those defects will be identified. Additionally, for comparison of same components specific factors for emission, transmission and reflection can be neglected as temperature differences for same materials are independent of these factors. Critical values for absolute temperature and temperature differences were already presented in [8].

Earth loop testing

The substation’s grounding is essential and should be verified during an inspection to gather information on its quality. Visual inspections can only assess parts above earth which is not adequate, as main components of grounding system cannot be analysed visually. To gather more reliable information on grounding system, measurement methods have to be used. For standardized measurement of grounding resistance the grounding connection of components has to be disconnected which is not allowed during operation. Alternatively, earth-loop testing is used to get more reliable information about the quality of grounding.

Earth-loop testing equipment generally induces a voltage in grounding conductor and measures the resulting current simultaneously. The resultant current is proportional to loop resistance, as long as the induced voltage is constant. The validity of the measurement increases the more parallel groundings exist [9].

This measurement method allows a reliable approximation of grounding resistance which means that maintenance potential can be derived correctly. Only the loop resistance is measured and comparisons with standardized measurement methods show approximate accuracies between 78 and 95 percent related to standardized conventional measurements.

SYSTEMATIC CONDITION ASSESSMENT

For systematic condition assessment an index for MV and LV components has to be determined using a valuation model. This model is already presented in [2] and is extended by the theory of evidence to take quality of the whole condition assessment into account. In that context quality of the condition assessment means that besides subjectivity of visual inspections even uncertainty of measurement methods has to be considered as well [2]. To determine specific values for uncertainty of measurement methods several laboratory tests were performed, because uncertainty of measurement methods is only assessed by results of field tests [2]. In the following section resultant uncertainty (results of field and laboratory tests) of acoustic PD detection will be analysed and presented as an example.

Uncertainty of acoustic partial discharge detection

Measurement errors of the used device for acoustic PD detection are not exactly specified by manufacturer. To get information on measurement deviations, extensive laboratory tests were performed having regard to detectability and accuracy of measured values. In the first step, detectability of acoustic PD detection is determined by a comparison of this measurement method and conventional PD measurement referring to IEC 60270. Conventional PD measurement is very sensitive and PDs can already be detected at an early stage [12]. Detectability of acoustic PD detection by using directional microphones mainly depends on the measurement distance between defect and microphone and its alignment. In practice measurement distance for acoustic PD detection at MV equipment is about $d = 80\ cm$ up to $d = 1\ m$. The same measurement distances were used in laboratory tests to determine the detectability regrading realistic conditions. Finally, laboratory tests confirm a high sensitivity of acoustic PD detection, but it is not as sensitive as conventional PD measurement. Regarding the quality of the condition assessment the detectability of that measurement has to be taken into consideration.

In the second step, multiple measurements with similar conditions and defects analysed by acoustic PD detection were performed to determine the measurement accuracy. The measurements show that the values deviate slightly, but these variations need to be considered in addition to detectability of acoustic PD detection as well. Deviations of measured values in transition areas of maintenance requirements may lead wrong results.Considering detectability and accuracy of acoustic PD detection leads to the whole uncertainty of the detection method which varies considering the identified maintenance requirement as shown in figure 4. Uncertainty declines with increasing maintenance requirements starting at 24 % up to 9 %. For systematic condition assessment even measurement errors of thermal imaging, earth-loop testing and visual inspections have to be considered, too [6].

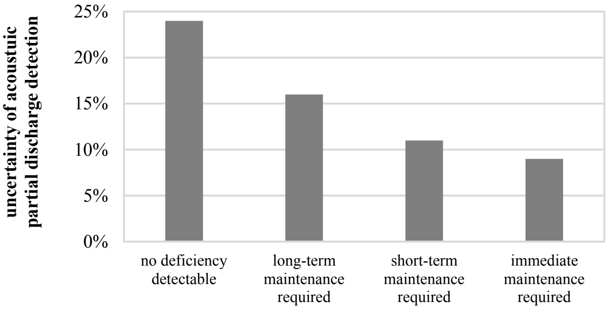

Figure 4: Uncertainty of acoustic partial discharge detection depending on maintenance requirements

Condition assessment considering uncertainty of visual inspections and measurement methods

As stated before, the quality of the condition assessment has to be considered by the valuation model. Therefore the existing valuation model has to be extended using the mathematical principles of the theory of evidence. The corresponding background is already presented in [2] and [10]. For condition assessment of MV and LV components best practicable mathematical method to combine two evidences - results from visual inspections and measurement methods - has been developed in [2].

Using theory of evidence information on maintenance requirement and its uncertainty are calculated [2]. To check practicability of the new approach the assessment model was used in numerous field tests for MV substations by several German DSOs, including LV distributions. Figure 5 shows results of calculated values.

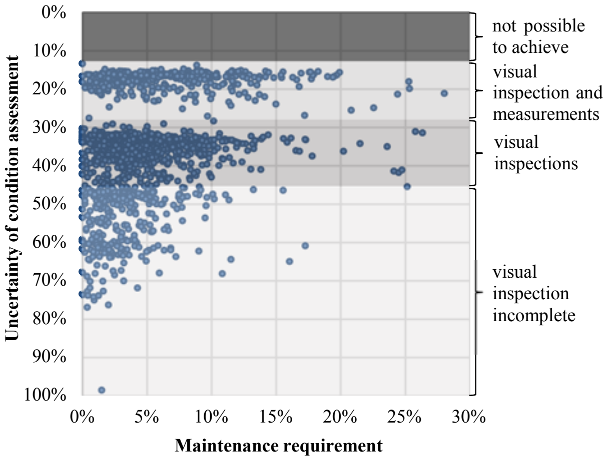

Figure 5: Results of field tests of MV substations considering maintenance requirement and uncertainty of condition assessment

Figure 5 allows the differentiation between all kinds of inspection: incomplete visual inspection, only visual inspection and combination of visual inspection and measurement analysis. If the condition assessment is incomplete or no measurement methods are used, the uncertainty will be pretty high. The most valid results are achieved by combining the presented measurement methods and visual inspections. Nevertheless in practice, an uncertainty lower than 11 % is not possible, because the applied methods still have an uncertainty themselves. Even more complex measurement methods (such as conventional PD measurement) will be needed to achieve a lower uncertainty measurement deviations and uncertainty of condition assessment.

CONCLUSION

In this paper the practical experience with the developed model for a systematic condition assessment of MV and LV components is presented. It is based on periodic inspections in an interval of one year up to four years. The indications of visual inspections („soft facts“) and of the measurement results („hard facts“) are combined – considering their specific significance/ uncertainty - to a realistic overall condition index. The integration of measurement methods lead to a well-founded and comprehensible condition assessment of electrical components. But especially regarding MV and LV level the effort for the assessment has to be taken into account. Therefore, measurement methods and their requirements for condition assessment of MV and LV components are presented in this paper. Additionally, the interpretation guidelines for the measurement values are also discussed.

In order to derive maintenance requirements from measured values various laboratory tests were necessary, since critical values for used measurement methods are not standardized at all. Critical values and interpretation guidelines for acoustic PD detection are presented. For thermal imaging analyses and earth loop testing see [6].

For condition assessment measurement methods have to be suitable to detect defects reliably. But detectability and accuracy of these have mostly been unknown so far. Hence, uncertainties of the methods are determined by intensive laboratory tests and numerous field tests considering detectability of measurement method and deviations of measured values. As an example, the uncertainty of acoustic PD detection as an input data for condition assessment is presented in this paper for the first time.

Finally uncertainty of visual inspections and even measurement methods are known which allows expressing the quality of condition assessment by using the theory of evidence. This theory determines the uncertainty of the assessment which is pretty high if the visual inspection of components is incomplete. It will decrease if visual inspection is complete or even supplemented by measurement methods. This approach expresses the uncertainty with concrete values and leads to a well-founded and actual technical asset condition. Thus, a solid basis for asset management is given considering condition index and quality of condition assessment. Additionally, the presented procedure is universal and can also be adopted for components of higher voltage level.

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