Electrical Measurements for HV-Insulations as Diagnostic Tool

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***Abstract* — For the economic use of high voltage equipment in electrical energy systems, the knowledge of the condition of the installed components is necessary. If this is known, the most economic maintenance strategies can be realized.**

Diagnostic techniques are applied to observe relevant parameters and are supposed to provide an early warning. That is the reason why different monitoring-, analysing- and diagnose systems become a fixed part in electrical power generation, transmission and distribution systems. So, within the last years, the demand of new monitoring and diagnostic equipment for the use at HV systems is increasing. One of the electrical methods of these diagnostics are dielectric, breakdown and partial discharge behaviour.

***Index Terms* — Electrical, optical PD measurement, partial discharge, isolation current method, dielectric diagnostics.**

I. Introduction

New development in the area of the signal measuring and conditioning, data processing and analysing as well as environmental aspects make a more precise and detailed condition evaluation possible. The use of monitoring and diagnostic systems depends from different factors. With these systems significant parameters are recorded and based on these measured variables (for example: temperatures, optical signals, electrical and mechanical measurement etc.), conclusions of the future behaviour of the technical resources can be made. The data acquisition can be split in on-line and off-line method. For the on-line method, the operating condition (voltage, current, load, temperature etc.) are used, in contrast to this, for the off-line method test generator supplies the examined equipment with different kinds of electrical stress.

The methods for condition determination of component and HV-equipment are manifold. The dielectric condition is related to the capability of the insulation to withstand high voltages and electric fields. A plenty of physical measured values and parameters are consulted, which gives directly or indirectly information about the dielectric condition. The electrical methods for diagnose are dielectric, breakdown and partial discharge behaviour. The observation and evaluation of the interaction between electromagnetic field and insulation material is named as dielectric diagnostic. Thereby the different polarization mechanisms and the reaction of the dielectric material at suitable voltage stress are registered. With breakdown analysis volume, weak spot and surface properties can be evaluated on insulation models or separated equipment.

At local inhomogeneous in the insulation discharges in small areas can occur. The appearance and the intensity of this partial discharge are a quality criterion for a rating of electrical equipment and an estimation of the condition of the insulation system can be done. For the partial discharge measurement electrical, acoustical, optical and chemical methods are possible. The electrical method is primary used for the detection, the acoustical and the optical method are used for the exact localisation of the PD.
PD diagnosis can be made as on-line and off-line measurement. Loss factor, insulation resistance, recovery voltage or polarization/depolarization current measurements are typically off-line methods, which give integral information on the insulation condition.

II. Basics

A. Dielectric Diagnostics:

The observation and evaluation of the effect between the electromagnetic field and the material is called dielectric diagnostics. The different polarization mechanisms and the reaction of the dielectric will be acquired. Material and device-specific parameters such as capacity, loss factor and insulation resistance give information about changes in the insulation medium. Thereby are the aims the detection of structural changes, humidity, pollution and electrical discharges.

B. Breakdown Diagnostics:

An over voltage, with defined peak and shape, is used as intensified operating condition for the examination of the insulation strength and to make a recognizing of structural changes and faults in the insulation possible. Different methods such as multiple-level test, successive discharge test and the up-and-down test are mentioned as examples. With these methods volume characteristics, weak spots and surface properties can be examined. This diagnostic method has a high expressiveness, but it has to be considered that the electrical stability of the whole system can be lost as consequence of a breakdown.

C. Partial Discharge Diagnostics:

The presence and the strength of partial discharges in electrical resources are criterions for the insulation quality. Partial discharge measurements will be used as non-destructive checks for the insulation of high-voltage resources during quality tests in the factory and in service. This is the reason why different techniques of partial discharges measurements are established as important diagnostic tools for detection and location.

III DIELECTRIC DIAGNOSTICS

The dielectric diagnostics include the measurement of the loss factor, the capacity as well as the insulation resistance. By the acquisition of these parameters, several limit values are examined during a non-destructive test procedure.

A. Insulation Resistance

The measurement of the insulation resistance gives information about the presence of insulation barriers. In the context of trend analysis, for example the aging and humidification of insulations with cellulose components can be pursued. The insulation resistance results from a resistance network as reproduction of the material and surface attributes.

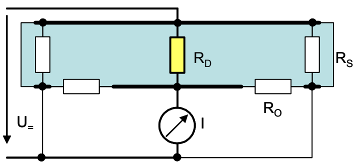


Fig. 1: Measurement of the conductance in a guard-ring arrangement [1]

With the guard-ring arrangement (Fig. 1), a separate evaluation of the volume resistance and the surface resistance of an insulating sample can be made.

B. Capacity and Loss Factor

The loss factor and/or capacity measurement are classical methods for the actual condition evaluation of insulating systems. The 0.1 Hz method is the established method for the onside evaluation, due to the low load power consumption. It gives important parameters for the aging condition evaluation of an insulation system. For a comparison, the measurement must be done at the same conditions than in the past.

The classical circuit for the evaluation of capacity and loss factor is a “C / tan δ” Schering Bridge. It is characterised by the fact that the object reality is stressed closed to high voltage, which can be measured (opposite usual alternating voltage bridges).

New computer-based measuring systems work according to the principle of a vectorial impedance measurement in the frequency range by analysing the fundamental harmonic of the currents [1]. Thereby the loss factor is determined from the phase shift of the current signals of a measuring branch and the comparison branch.

C. Isothermal Relaxation Current Analysis (IRC)

The isothermal relaxation current analysis (IRC-Analysis) offers a destruction free possibility to investigate the degradation processes of polymeric composites, which are the base materials in modern insulation systems (cables).

The IRC-analysis is based on the measurement of the depolarization current after previous forming with DC voltage. With the help of mathematical procedures, different rates of the relaxation current with the respective time constants are determined and represented in an IRC-Diagram. This diagnostic method provides a global statement about the insulation system. It requires a reference value from the past to show the condition changes of the insulating system. The relaxation current represents a superposition of different current components. These components - with different relaxation times - depend on specific mechanisms of charge trapping and ageing [2].

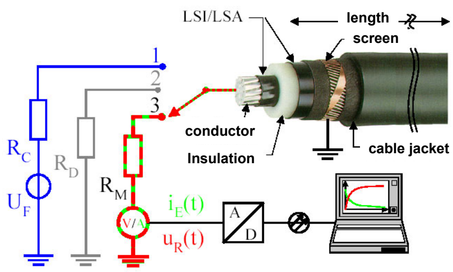


Fig. 2: Measurement principle of the IRC-Analysis [3]

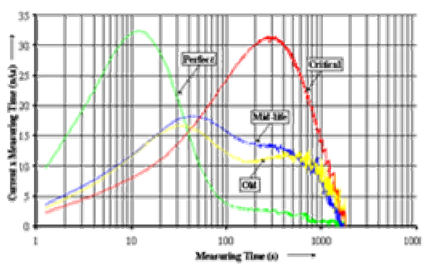


Fig. 3: Examples of IRC results of differently aged cables [4]

Fig. 2, 3 show the principle of the IRC-Measuring circuit. With the formation of the polymeric volume with a DC-voltage, it is possible to measure the isothermal relaxation current i(t) after discharging the transient parts of the current. An isothermal current measurement time interval of 5 to 1800 s after the DC forming is used. Performing the IRC-Analysis, several relaxation current components with time functions correlating to the physical structure of the test device can be associated. Therefore the isothermal relaxation current i(t) is evaluated by a specially selected number of the dependent relaxation current components.

$$i(t) = I_0 + \sum_{i=1}^{n} a_i \cdot e^{-\frac{t}{\tau_i}} \qquad (1)$$

The coefficients and the weighting factors of these current components are calculated with an intelligent approximation algorithm [2].

D. PDC-Method (Polarisation / Depolarisation Current Analysis)

The PDC-measurement (polarization / depolarization current measurement) is a new modern measuring procedure for the evaluation of the insulation system (power transformers and cables). The procedure uses DC voltage to test the specimen. From the DC voltage step a polarization / depolarization current results in the insulating medium, which decays exponentially. The PD current is typical in the nA- range. The temporal process, the size and the shape of the PD current give information about condition and characteristic values (oil conductivity, polarization time constants).

At a transformer, a DC voltage step is applied between OS and US coil during a certain time TL the so-called polarization duration (Fig. 4). Thus, a charging current of the insulation system capacitance, the so-called polarization current, flows.

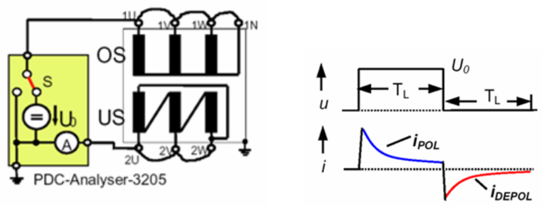


Fig. 4: Measurement of the current and the principle distribution [5]

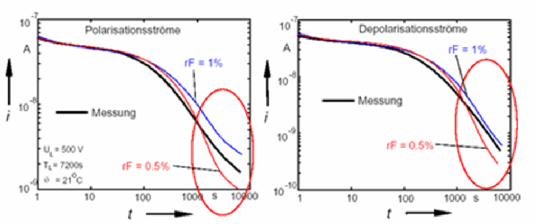


Fig. 5: PDC-Analysis of example a transformer [6]

It is a pulse-like current during the instant of voltage application, which decreases during the polarization duration to a certain value given by the DC conductivity of the insulation system. After elapsing the polarization duration TL the switch S goes into the other position and the dielectric is short-circuited via the ampere meter. Thus, the discharging current jumps to a negative value, which goes gradually towards zero. Both kinds of currents, called relaxation currents, are stored in the PDC Analyzer Instrument [5].

The PDC-Analyzer is an instrument for on-site measuring and analysing of the dielectric behaviour of electrical insulation materials and insulation systems. All kinds of insulation materials are subjected ageing effects or degradation processes, when stressed with electric fields, temperature, partial discharges and/or mechanical load. These ageing effects influence the dielectric properties, and can be identified either by several measurements (“dielectric response function”, “time domain spectroscopy”, “frequency domain spectroscopy”). With the PDC-Analyzer, the possibility to transform each measurement method mathematically into equivalent results of the other method is given. The PDC-Analyzer is based on “time domain spectroscopy”, which can be made in less time and with better precision than measurements in the very low frequency domain. Therefore, the PDC Analyser is a flexible diagnostic tool for insulation systems and materials and it can be used in high voltage substations as well as in laboratory and industrial environments.

E. Frequency Response Analysis (FRA)

The frequency response analysis is a powerful diagnostic test technique and will be used as a mechanical and electrical fault detector. It consists of measuring the impedance of transformer coil over a wide range of frequencies and comparing the results of these measurements with a reference set. According to the electro technique theory, the principle is that a transformer coil system is equivalent to a passive network (Fig. 6). The characteristic of this network can be described by the transfer function. All faults that alter the distributed capacitance or inductance parameters of the windings can be detected by measuring the frequency response at the terminals of transformer windings.

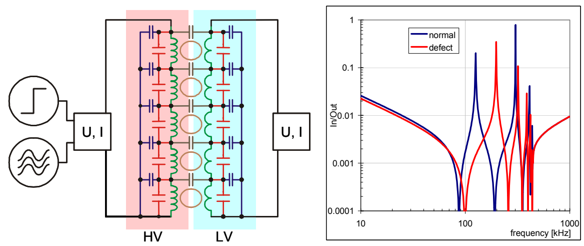


Fig. 6: FRA Results for Case Study

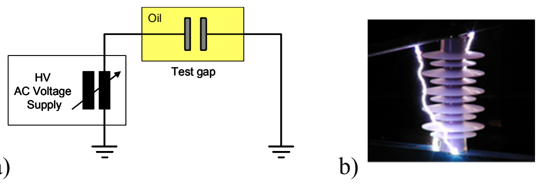
FRA techniques need sophisticated instrumentation and analyzing software algorithms over a wide frequency range. A large number of factors affect the result and can lead to an uncertain conclusion. In addition, it is not possible to implicate the degree of the winding damage to the change of the transfer function. The main motivation is the reliability and sensitivity of major and minor fault detection. The main disadvantage is the interpretation and analysis with reference to faults. The transfer function varies with each individual transformer and the connected power equipment.

Differences may indicate damage to the transformer, which can be investigated further using other techniques or by an internal examination.

IV Breakdown Diagnostic

This test method covers procedures for the determination of dielectric strength of insulating materials under specified conditions. Thereby weak points in the material or construction can be point out on test models or on whole components.

The basic idea of a breakdown voltage test is to apply current limited high voltage to an insulator or insulation material, and raise the voltage until the desired test level is reached. If the capability of the medium or device to resist the supplied voltage, a breakdown takes place with an electrical arc or spark. The test generator should limit the current flow, thereby the energy of the arc is limited without excessive damage at the void area and further investigations can be done.



a) b)

Fig. 7: a) Breakdown test for liquids b) Support insulator - Flash over

Several voltage shapes (constant, step or ramp value) are in use for the breakdown diagnostics. The withstand voltage can be evaluated with the constant voltage, the increasing voltage or the “up-and-down” voltage test for self-healing material such as gas or liquids (Fig. 7). At solids, a breakdown leads to a destruction of the material and a loss of the device.

V. Partial Discharge Diagnostic

Partial discharges are local enhancements of the electric field in the area of inhomogenities, either in gaseous, liquid or solid media. Partial discharges have only a small short time influence on the electrical firmness of electrical resources. On the other side, the long time influence shows a destructive effect predominantly on organic insulation systems, which degrade the electrical characteristics of the insulation or the insulation systems. This can lead to a breakdown and a failure of the concerning resource.

A multiplicity of different PD sources and PD features with characteristic properties as well as overlays of PD places high requirements against to the diagnostic system.

For the measuring, physical effects, such like optical, electrical and acoustical appearances, will be used. Different measuring methods depending on the electrical equipment are used for the PD behaviour analysis (Fig. 8).

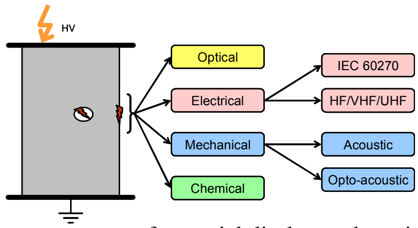


Fig. 8: Category groups for partial discharge detection

A. Conventional Measurement of Partial Discharges

By the conventional PD measuring technique, measuring circles according to the guidelines of the IEC 60270 are used. Beside the high voltage source, the test setup contains a couple-capacitor and a measuring impedance. Each partial discharge in the test specimen causes a short high frequency current pulse in the measuring circuit. The measuring impedance couples this impulse out and the following measuring system can be implemented as narrow-band, limited wide-band or wide-band system. The used measurement systems detect the apparent charge, the phase position to the test voltage and the number of discharges over a given gate time interval. Further parameters can be calculated by using the stored data.

B. UHF Measurement of Partial Discharges

Partial discharge impulses of very short duration (< nanoseconds), produce electromagnetic waves, whose spectrum reaches up to the GHz range. In coaxial structures (e.g. GIS, GIL), this impulse releases electromagnetic waves. For this reason capacitive sensors, as like antennas, were developed, which can detect transient waves (Fig. 10).

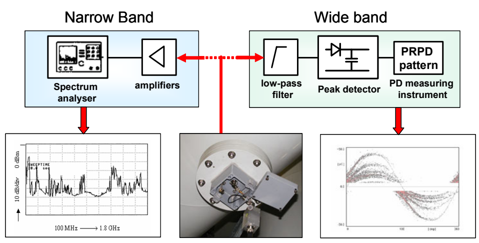


Fig. 9: UHF PD Measurement

Two different kinds of detection systems (Fig. 9) are used, the narrow band system with a frequency range of some MHz and a wide band system up to 2 GHz

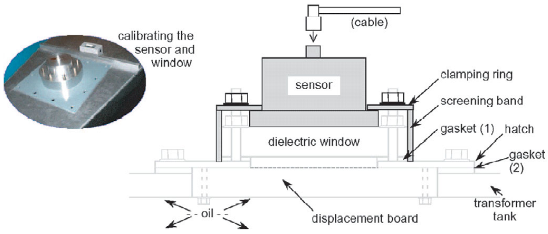


Fig. 10: A UHF window retrofitted to a transformer inspection hatch [7]

C. HF/VHF Partial Discharge Measurement

Partial discharges in polymeric insulations show a duration of several nanoseconds at the point of origin. A transformation of the time signals in frequency domain shows a constant amplitude curve of the PD frequency spectrum up to the range of 100 MHz. For the measurement, inductive and capacitive sensors are used.

By the example of an inductive PD measurement, a toroidal inductor encloses the energized conductor (e.g. cable), into whom the temporally rapidly changing current induces a proportional voltage. The advantage of this method is the galvanic separation from the high voltage during the acquisition of the PD current, as well as the exact fault location by shifting the coil.

D. Acoustic Partial Discharge Measurement

Each partial discharge delivers energy, which can be detected as sound (pressure wave). Depending on combination of the surrounding media, it comes to an influence of the propagation speed of the acoustic wave. Likewise, reflection and refraction as well as absorption by dispersions and absorption lead to changes of sound propagation, which must be considered during detection and interpretation (Fig. 11). The main field of application of this method is the detection of defective areas of equipment. Microphones, just like piezoelectric transducers, are used as sensors.

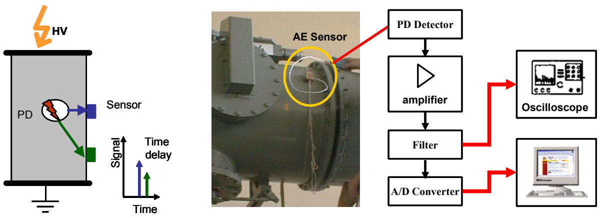


Fig. 11: Principle schematic and acoustic PD detection system

E. Opto-acoustic Partial Discharge Measurement

During a partial discharge in gas or oil, it comes to an acoustic wave into the sonic and ultrasonic range. If the developed wave affects a special optical fibre, its optical transmission characteristics are changed. This fact is used by the opto-acoustical sensor principle. If a PD in the surrounding medium arises, the pressure wave results in a deformation of an optical fibre. It comes to a mechanical stress and a stretch of the fibre and thus to an influence of the used polarized light by this fibre too. It comes to a change of the optical distance as well as the polarization condition [8].

F. Optical Partial Discharge Detection

The optical partial discharge detection is based on the detection of the light produced as a result of various ionization, excitation and recombination processes during the discharge. The amount of the emitted light and its wavelength depend on the insulation medium (gaseous, liquid or solid) and by different factors (temperature, pressure …). The spectrum of the light emitted by partial discharges depends on the surrounding medium. The optical spectrum reaches from the ultraviolet over the visible into the infrared range (Fig. 12) [10].

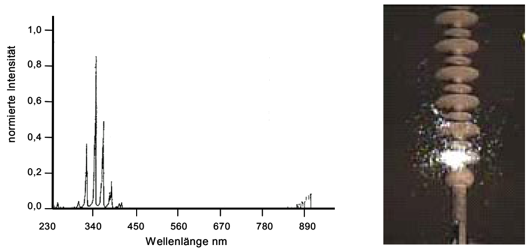


Fig. 12: Spectrum of the emitted light (air)

UV radiation emission measurements and observations with a night-vision device for detection of corona and other electrical discharges on surfaces are used. With the help of a daylight UV inspection camera corona and arc localization can be accomplished at high voltage transmission lines and in power stations.

The camera has two representation channels and contains an UV sensitive channel for the corona discharge and the second within the visible range for the admission of the environment. Both images are superposed and result in a video picture (Fig. 13).

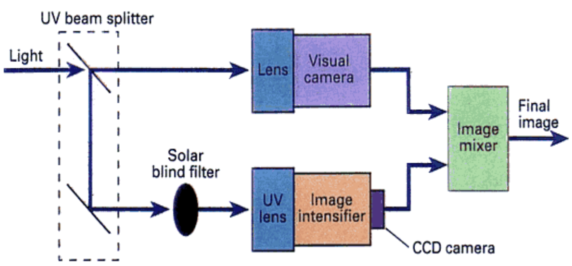


Fig. 13: Operation diagram camera DayCor II™ [9] and application

G. Chemical Partial Discharge Detection

Chemical methods for the measurement of the PD activity act as an integral procedure for the determination of decomposition products in the insulation medium, caused by partial discharges. In insulating liquids usually gaseous compounds are developed, which can be determined with the help of the Gas-in-Oil analysis. Thereby the developed fission gases depend on the power density as well as the insulation materials. If partial discharges occur in air, the chemical reactions between the components of air accumulate NOX and ozone. The determination of ozone concentration makes conclusions concerning the partial discharge activity possible, for example air-cooled machines. A disadvantage of the chemical procedures is the integrative character. So it is not possible to indicate the apparent charges of a single partial discharge, number of discharge or to locate their point of origin.

VI. CONCLUSION

The early recognition of changes in the insulation system increases by the use of new technologies.

For the diagnosis it is very important to know the composition of the insulating material of the different equipment and systems. The data acquisition by monitoring systems, the data transfer and storage according to accomplished analysis and trend evaluation becomes a fixed part of the equipment of reliable diagnostic systems.

Sensors concerning quality and variety and the use of new physical effects make it possible to carry out new developments in the area of the technical diagnostics. Integration of the sensors in components of energy engineering with signal pre-processing and an improvement of the assigned systems concerning reliability, efficiency and user comfort are set as aim. As examples, the range of the partial discharge diagnostics with the conventional measuring technique and in increasing degree the employment of unconventional acquisition methods can be mentioned.

In addition, the application of a reliable diagnostic system presupposes the support of the service personnel and information from the past of the operational equipment. Therefore, it is possible to save costs and increase the reliability and availability of the power system.

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