Electrical Measurements as Diagnostic Tool for HV-Insulations

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Abstract: *The electric condition is related to the capability of the insulation to withstand high voltages and electric fields. The methods for condition determination of component and HV-equipment are manifold. A plenty of physical measured values and parameters are consulted, which gives direct or indirect information about the equipment condition. With equivalent mathematical combination and analyse functions, an early diagnosis of an initiated system fault can be made.*

Diagnostic techniques are in use to observe relevant parameters and are supposed to provide an early warning. Different diagnostic methods (thermal, mechanical and electrical) and systems (Online - Offline) of power equipment will increase the reliability in service.

The electrical methods of this diagnostics 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 a suitable voltage stress are registered.

With breakdown analysis volume, weak spots and surface properties can be evaluated on insulation models or separated equipment. The appearance and the intensity of partial discharge is a quality criterion for a rating of electrical equipment and an estimation of the condition of the insulation system can be done. The purpose is the detection of structural changes, humidity and contamination during the service life.

1 Introduction

For the economic use of high voltage equipment, it is necessary to evaluate the condition of the used components. If the condition is known, the most economic maintenance strategy can be realised. Inspections can be planned on a long-term basis and the component lifespan can be fully used. This is the reason why monitoring-, analysing- or diagnostic systems become a fixed part in power generation, transmission and distribution systems.

A so-called "expert diagnostic system" should make, after the recognition of a disturbance, an automatic case identification of the disturbances source. With help of appropriate procedures, the diagnosis permits an evaluation, which goes beyond to summary of the obvious signs of defects. The reliability of the connection between this indication and the derived pattern is important for the usefulness of the assigned diagnostic procedure [1] [2] [3]. Different methods, which acquire the multiplicity of physical dimensions e.g. temperature, conductivity and radiation into a database for the diagnosis, are used.

2 Basics

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, dissipation factor and insulation resistance give information about changes in the insulation medium. Thereby aims are the detection of structural changes, humidity, pollution and electrical discharges.

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.

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.

3 Dielectric diagnostics

The dielectric diagnostics include the measurement of the dissipation 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.

3.1 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.

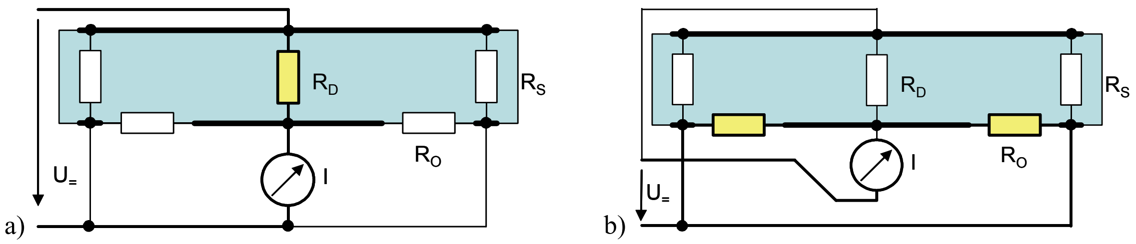

Fig. 3.1: Measurement of the conductance (a) and surface resistance (b) in a guard-ring arrangement [1]

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

3.2 Capacity- and dissipation factor

The dissipation 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, because of 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.

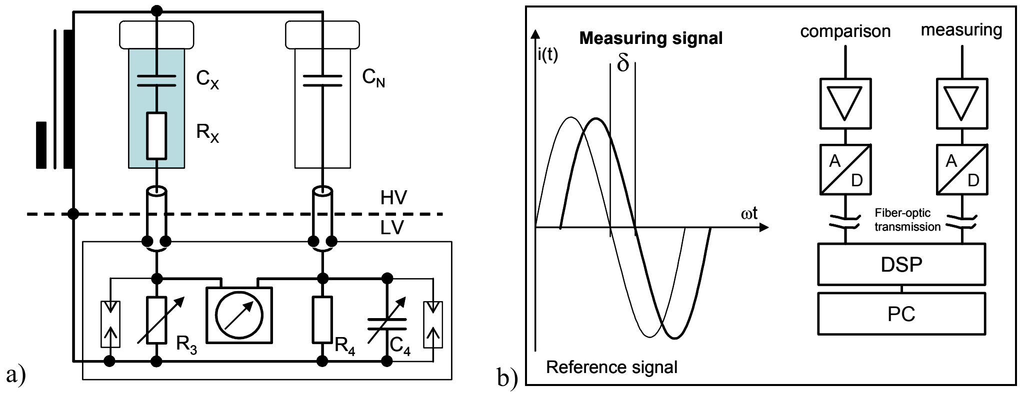

Fig. 3.2: a) Capacity and dissipation factor measuring with Schering Bridge,
b) PC based measurement of the dissipation factor [1]

The classical circuit for the evaluation of capacity and dissipation 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 dissipation factor is determined from the phase shift of the current signals of a measuring branch and the comparison branch.

3.3 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.
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. Computer algorithms can separate the parameters [6].

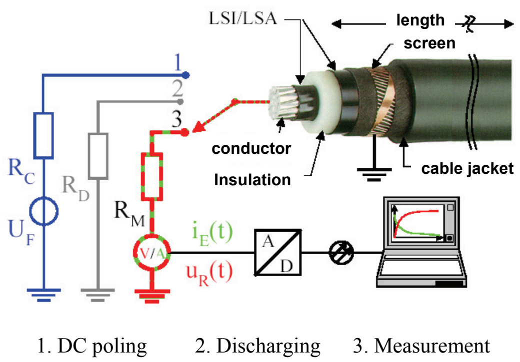

Fig. 3.3: Measurement principle of the IRC-Analysis [4]

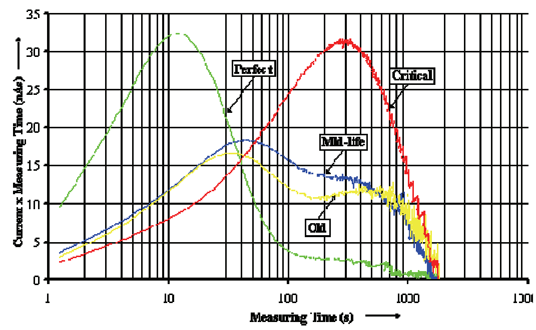

Fig. 3.4: Examples of IRC results of differently aged cables [5]

Fig. 3.3 shows 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 and an isothermal current measurement time interval of 5 to 1800 s after the DC forming. 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.

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

The coefficients and the weighting -factors of these current components are calculated with an intelligent approximation algorithm [6].

3.4 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 T_L the so-called polarization duration (Fig. 3.5). Thus, a charging current of the insulation system capacitance, the so-called polarization current, flows.

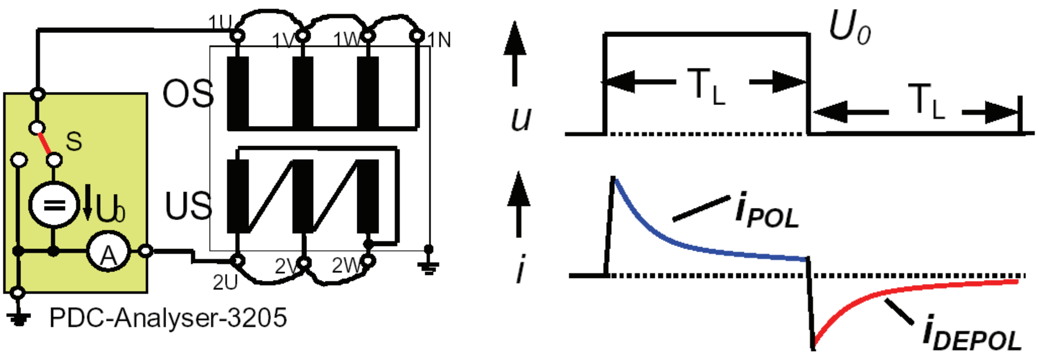

Fig. 3.5: Measurement of the current and the principle distribution [7]

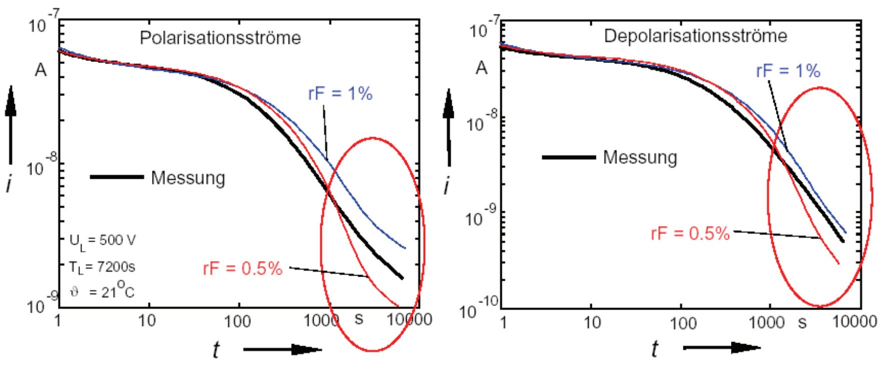

Fig. 3.6: PDC-Analysis of example a transformer [8]

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 T_P 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 [7].
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 affect the dielectric properties. These can be identified either by several measurements ("dielectric response function", "time domain spectroscopy", "frequency domain spectroscopy"). With the PDC-Analyzer, you have also the possibility to transform each measurement method mathematically into equivalent results of the other method.
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.

3.5 Frequency Response Analysis (FRA)

The frequency response analysis (FRA) is a powerful diagnostic test technique and will be used as a mechanical 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. 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.

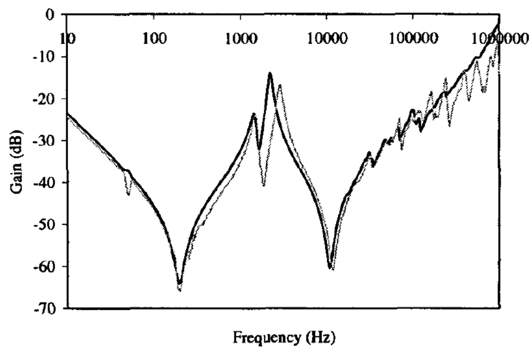

Fig. 3.7: FRA Results for Case Study [18]

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.

4 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.
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. At solids, a breakdown leads to a destruction of the material and a loss of the device.

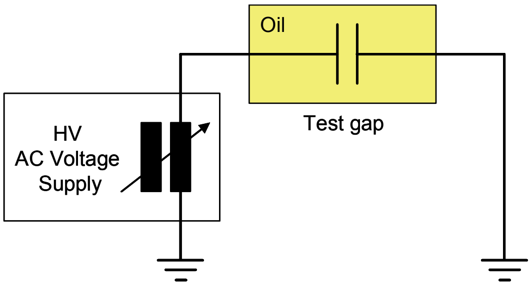

Fig. 4.1: Breakdown test for liquids

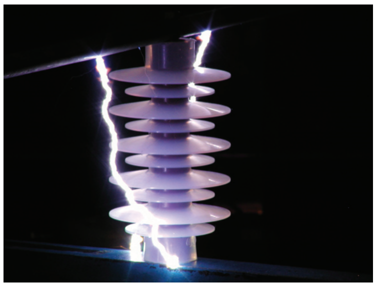

Fig. 4.2: Support insulator - Flash over

5 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.

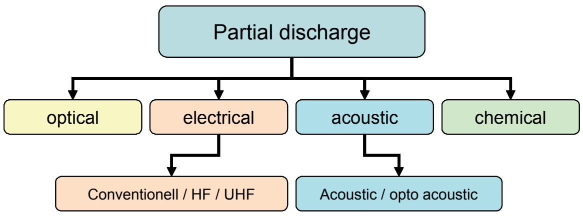

Fig. 5.1: Category groups for partial discharge detection

5.1 Conventional Measurement of Partial Discharges

With the conventional partial discharge measuring technique, measuring circles due to the guidelines of the IEC 60270 are used. Beside the high voltage source, the test set up 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. By stored data, further parameters can be calculated.

5.2 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.
Two different kinds of detection systems are used, the narrow band system with a frequency range of some MHz and a wide band system with a band wide up to 2 GHz.

Fig. 5.2: Externally mounted UHF sensor on the tank of a 1000 MVA transformer [9]

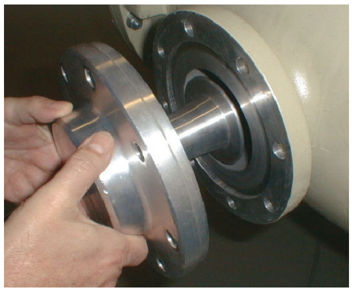

Fig. 5.3: Sectional view and mounting of an UHF PD disk sensor [11, 12]

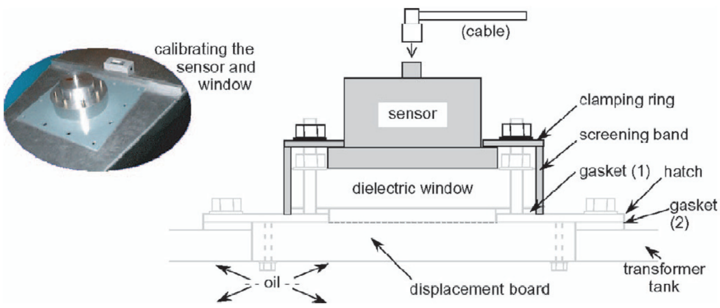

Fig. 5.4: A UHF window retrofitted to a transformer inspection hatch [9]

5.3 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.

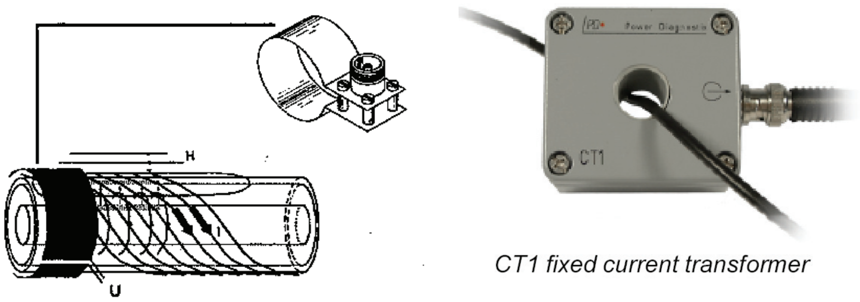

Fig. 5.5: Inductive impulse acquisition [16, 17]

5.4 Acoustic partial discharge measurement

Each partial discharge delivers energy, which can be detected as sound. 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. 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.

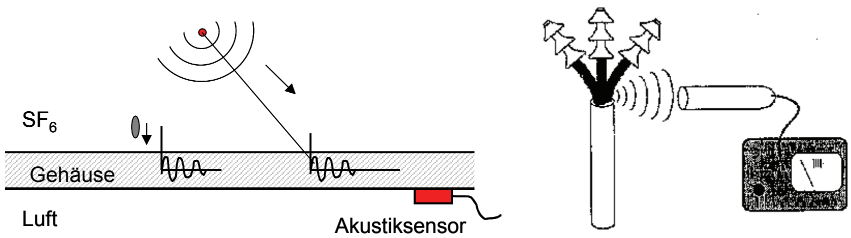

Fig. 5.6: Principle schematic to the acoustic PD detection

Fig. 5.7: Ultrasonic measuring instrument with directional microphone

5.5 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 [13].

5.6 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 [14].

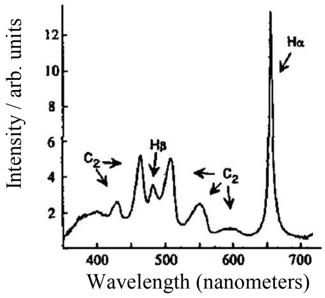

Fig. 5.8: Spectrum of the emitted light (oil) [10]

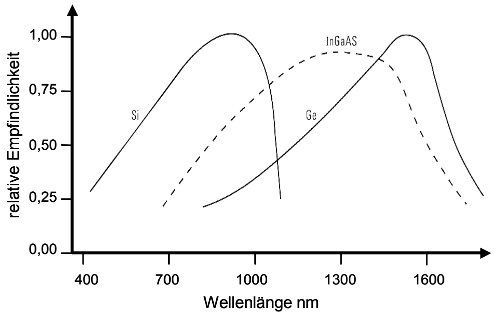

Fig. 5.9: Relative spectral sensitivity as a function of the wavelength of different detector materials

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 (see Fig. 5.10).

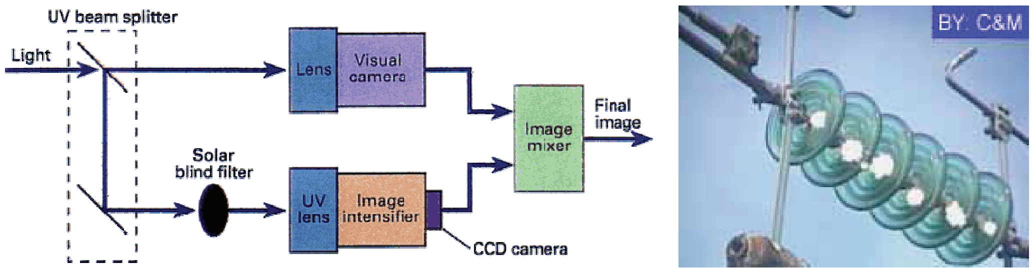

Fig. 5.10: Operation diagram camera DayCor II™ [15] and application

5.7 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 connections 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 NO_X and ozone. The determination of ozone concentration makes conclusions concerning the partial discharge activity possible, for example air-cooled machines. However, the disadvantage of the chemical procedures is the integrative character, which does not allow statements about the current operating condition. In addition, it is not possible to indicate the apparent charges of a single partial discharge or to locate their point of origin.

6 Conclusion

By the use of new technologies, the early recognition of changes in the insulation system increases. However, the knowledge of the insulating material of the different equipment and systems are very important for the diagnosis. 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.

7 Literature

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