Abstract—Condition monitoring and diagnosis of the components of electric power systems are important for reliable power transmission and distribution. The insulation systems of the electric power system are submitted to aging processes and the reduction of the performance of the insulation system causes failure like breakdown or flashover. In order to reduce the risk of an unexpected outage the exact knowledge of the condition of the insulation system is very important. The various insulation systems require different monitoring techniques and diagnosis. Starting with the description of the condition monitoring and diagnosis methods for gas insulated components, the various methods for solid and liquid insulation systems as well as the combination solid-liquid will be described. The disadvantages and the advantages together with the limits of the monitoring and diagnosis systems concerning sensitivity, reliability and reproducibility will be described.

Keywords – Condition monitoring, diagnosis, insulation systems, electric power system

I. INTRODUCTION

The demand on energy is increasing worldwide and the demand on electrical energy too due to the big advantages of electrical energy like simple generation, transmission, distribution and use. The share of electrical energy on the total amount of energy is also increasing and more or less the whole industry and infrastructure depends strongly on the availability and reliability of the electric power system.

The electric power system can be described according to the energy flow from the power generation with a rotating machine (generator) or a photovoltaic system via a step-up transformer to a transmission system and then via a step-down transformer to a distribution system and finally to the users, where the electric power can be used for driving electrical machines (motors), heating, lighting and supply for all kind of communication and information equipment.

The requirements on the availability and reliability on one side and on the economy on the other side lead to the situation that the utilities as well as the user of the electric power system should know the actual performance of the components in the electric power system. Therefore the utilities are working intensively on the asset management and are always looking for reasonable and efficient tools. Furthermore the environmental impact should be taken into account when components of the electric power system have to be replaced or when new generation, transmission or distribution systems are planned.

The monitoring of the condition of the components of the electric power system is the basis for the diagnosis. Monitoring means recording of various data of the equipment, which can be temperature, pressure, mechanical load, torque, electrical and dielectric parameters like e.g. partial discharges (PD) or chemical parameters like gas-in-oil analysis or physical parameters like surface tension. The evaluation of the recorded parameters and its combination may lead to a diagnosis, which means the capability to recognize the actual performance and to take decision for further measures.

The performance of the components of electric power systems depends on their mechanical, thermal, electrical and environmental stress and for each stress specific parameters should be taken into account for monitoring and diagnosis. The following contribution will be concentrated on the monitoring and diagnosis of insulation systems, which exist in all high voltage apparatus of an electric power system.

II. GASEOUS INSULATION

The natural gaseous insulation is air and the parameters concerning the electrical behaviour are temperature, pressure and humidity. These parameters are easy to monitor, but can not be influenced in general and therefore the apparatus have to be designed according to the relevant limits.

A. Overhead lines

The transmission capacity of an overhead line depends also on the temperature of the conductors. In order to use the overhead lines in an efficient way the temperature of the conductors could be recorded and the load can then be adjusted to the actual temperature [1]. The influence of the cooling due to wind and the weather forecast may be also taken into account for the planning of the power transmission. This kind of monitoring contributes to an efficient use of existing systems, preventing in some cases installations of new transmission systems and saving resources. Here no diagnosis is required because the performance of the air as insulation system depends only on the physical parameters like air density and air pressure assuming that the electrical field configuration is unchanged.

B. Gas insulated systems

The most used gas in high voltage apparatus is sulphur hexafluoride SF₆ due to several advantages as high breakdown voltage, non-toxic, inert and chemical stable. The disadvantage is the high potential regarding the greenhouse effect; therefore research activities are ongoing to replace SF₆.
or to reduce the amount of SF₆ in the high voltage apparatus. It should be differentiated between the use of SF₆ as insulating material like in Gas Insulated Lines (GIL) or Gas Insulated Substations (GIS) and the use in circuit breakers, where beside the insulation the extinction of the arc under high pressure is required. For this purpose no substitution for SF₆ is available at the moment. The monitoring of gas insulated systems comprises the recording of the gas pressure or better gas density, the dew point as well as the temperature. The electrical data like voltage and current will be also recorded, but this data is always available.

SF₆ shows no ageing behaviour and therefore the monitoring of the pure gas is not reasonable, but the gas can be decomposed by electrical discharge processes like PD and then the electrical performance will be reduced and may lead to a breakdown or flashover within the gas insulated system. Therefore the monitoring of PD activities within a gas insulated system is very often required and several monitoring techniques are available. The traditional PD measurement via coupling capacitor according IEC 60270 [2] is possible but very often the sensitivity is not high enough to detect the small PD sources, particularly on site where the noise level could be very high [3]. Therefore the so called Ultra High Frequency (UHF) PD measurement was introduced many years ago and is nowadays a more or less common monitoring procedure [4]. The method is based on the fact, that a gas insulation system is a coaxial arrangement and that PD generates different kind of signals like optical, acoustical and high frequency electromagnetic waves. These waves are travelling within the gas insulated systems similar to a coaxial arrangement and can be detected via high frequency sensors. Fig. 1 shows an example of the frequency content of PD in the UHF range.

The sensors can be installed at different places of the gas insulated system without influencing the electrical field distribution inside the system. The electromagnetic waves are attenuated by the spacers and also influenced by the arrangement like junctions. A comparison between the measurements according to IEC 60270, where the PD activities are given in pC as apparent charge and a calibration in pC is possible, and the UHF method, where the PD activities are given in arbitrary units, is not possible and therefore only a sensitivity check is possible, but also very helpful for the diagnosis [6]. Fig. 2 shows a measurement on a gas insulated substation with UHF method, where the signal to noise ratio is good in the high frequency range.

The acoustic method can also be applied on gas insulated substations, but also this method is not comparable with the conventional method according IEC 60270. The sensitivity is also limited by the distance between the PD source and the sensor location. The simple positioning of the acoustic sensors is often used for the localization of PD sources inside gas insulated systems.

C. Insulators

Insulators are made of porcelain or composite materials like epoxy resin and silicone. They are used as supporting device or as cover of a bushing, instrument transformer, surge arrester etc. The performance of the insulator under the environmental conditions depends mainly on the design of the envelope regarding creepage distance and the flashover distance. The humidity and the pollution of the surface of the insulator are the most important parameters regarding the flashover voltage of the insulators. Several attempts have been made for the monitoring of the surface condition, e.g. the measurement of the leakage current and the loss factor [7]. Also the measurements of the harmonics of the leakage current would be proposed as a measure to identify the flashover performance.

III. LIQUID INSULATION

Here in this chapter the pure liquid insulation systems should be dealt with, even if in real components of an electric power system the combination liquid-solid insulation systems is always used. Numerous research activities are involved in the investigation of liquid insulating materials together with the evaluation of parameters which allows determining the ageing and the remaining performance of the insulation material in order to get information of the remaining life time under service conditions.

A. Mineral oil

The dielectric performance of mineral oil is mainly influenced by the water and gas content dissolved in the fluid. Fig. 3 shows the breakdown field as function of the relative humidity.
which is given by the ratio of the absolute humidity to the saturation humidity at the relevant temperature.

For that reason the usual procedure to monitor the quality of the fluid is to take a sample in regular time interval, e.g. annual, and to evaluate the parameter like colour, humidity content, breakdown voltage, tan δ, interfacial tension, acidity, inhibitor content, density, flash Point and viscosity. The liquid may also be used as sensor for the behaviour of the complete insulation system regarding the gas-in-oil analysis (DGA), but this will be dealt with in chapter V.

The ageing in general will be influenced by the thermal, electrical and dielectric and chemical degradation. The electrical degradation depends on the electric field strength and this is given by the design. The electrical stress may be influenced by the voltage shape due to the nonlinear voltage distribution depending on the frequency, but this can not be monitored in a reasonable way. A local field stress exceeding the performance of the insulation can be recognized by the partial discharge (PD) measurement and this technique will be described in detail in chapter IV. The thermal and in most cases the combined chemical degradation depends strongly on the temperature. Fig. 4 shows the ageing behaviour as function of the fluid temperature.

One curve is based on the assumption that a difference of 6 °K doubles the ageing factor, the other curve that a difference of 8 °K has this effect. In both cases the increase of the ageing factor with increasing temperature is enormous and should be taken into account, if the fluid temperature reaches a certain value.

B. Ester fluids

The use of ester liquids, natural or synthetic, becomes more and more important due to stronger environmental requirements and due to the advantages in some characteristics compared mineral oil. It should be mentioned that the ester fluids are not always better than mineral oil and one important point is the ageing behaviour of these fluids which is not as good known as for mineral oil and the need to add some kind of so called additives. One advantage is the high water solubility which leads to a low relative humidity at normal moisture content. Fig. 5 shows two different ester fluids in comparison to mineral oil regarding the water saturation point.

Water or humidity may be less important for ester fluids but all the other procedures concerning the evaluation of the ageing behaviour are comparable with the procedure for mineral oil.

IV. SOLID INSULATION

Solid insulation systems are required for mechanical purposes and are usually combined with gaseous and liquid insulation material. The weakest points in such insulation arrangements are the boundaries between the two or in some cases three materials, but monitoring and diagnosis an insulation system includes also the effect on the boundaries and they can usually not separated from the effect in the pure material.

In high voltage components the most used solid insulation materials are paper, pressboard, cross-linked polyethylene (XLPE), epoxy and composite (synthetic) materials. These materials are influenced by thermal, electrical and mechanical stress and in some cases also by chemical stress. Due to the different stresses and the different sensitivity on these stresses a number of monitoring and diagnosis procedure are available, e.g. the PD sensitivity of XLPE is much higher compares to an insulation system for rotating machines combined of mica and epoxy resin.
In the following some of the main monitoring and diagnosis system will be described in detail. The PD measurement is a very sensitive and non destructive method to find some points within the solid insulation which are stressed or overstressed by the local electric field and where discharges occur. The representative model is a small void within the solid insulation which is stressed by an electric field higher than the electrical field in the surrounding solid material due to the different permittivity in case of AC voltage is applied. If DC voltage is applied the permittivity may influence the voltage distribution and the electrical field much stronger. Fig. 6 shows the simplified schematic diagram.

![Simplified schematic diagram](image)

Figure 6. Simplified schematic diagram – left: test sample with void – middle: equivalent electrical circuit – right: simplified electrical circuit

If the applied voltage across the void, represented by the capacitor $C_1$ is higher than the breakdown voltage, the voltage collapse and the capacitor is discharged resulting in a current pulse due to the change of charge of the capacitor $C_s$.

![Voltage and current shape of PD activities](image)

Figure 7. Voltage and current shape of PD activities

In the upper part of Fig. 7 the voltage across the capacitors $C_p$ and $C_1$ is shown for the case that the PD exists, which means no discharge of capacitor $C_1$. The middle part shows the voltages in case of PD and the lower part the measured current pulses from which the apparent charge can be evaluated.

The charging of the capacitor $C_1$ can be done via an external coupling capacitor and the current pulse which delivers the charge can be measured via a resistor and this gives a signal related to the discharge parameter within the void. In real apparatus the charge which will be delivered from the coupling capacitor and which can be measured is called apparent charge due to the fact, that the required charge is not only delivered by the measurable charge but also by the not measurable charge coming from different sources like other capacitors, e.g. $C_p$, or from the voltage source. Even under these conditions the apparent charge is a good measure for the evaluation of the processes inside the insulation system and will be used for acceptance test as well as for monitoring and diagnosis. The weak point may be the missing correlation between the apparent charge or its derivates and the remaining life time of the insulation system.

In some cases not only the apparent charge but also the location of the PD source is of interest. The PD generates an electro-magnetic wave and the travelling time can be used to determine the location of the PD sources. In apparatus like gas insulated systems (GIS) the travelling waves will be distorted by spacers, branches or elbows and therefore the localization will be done by a number sensors distributed within the GIS. Fig. 8 shows an example of the distribution of sensor on a GIS. However this discussion is going how much sensors are really required for the PD monitoring of a GIS.

![Test arrangement of a GIS for sensitivity check](image)

Figure 8. Test arrangement of a GIS for sensitivity check [6]

A much simpler task is the localization of a PD source in a high voltage cable. The PD signal travels in two directions, to the measuring place and to the open end, where it will be reflected and the reflected signal travels also to the measuring point. The time delay between these two signals allows the exact calculation of the PD location assuming the characteristic travelling time in the insulation material and the complete length of the high voltage cable are known. In high voltage XLPE cables the weakest part are the cable joints and the cable terminations. Therefore the joints are equipped with PD sensors which allow the determination of the travelling direction of the PD source and the decision if the PD is within the cable joint are outside the cable joint in the cable insulation. Fig. 9 shows a cable joint with the two sensors used for the detection of the PD signal as well as for the travelling direction of the PD signal.
Another technique is the use of so called Rogowski coils near the cable joint if the cable joint has no in built sensors. Here again the travelling direction gives the information concerning the PD location in or outside the cable joint. Fig. 10 shows the arrangement as well as the measured signals.

The polarity of the output signal of the sensors (ROGA or ROGB) depends on the travelling direction of the PD signal and therefore the decision concerning PD inside or outside the cable joint is very simple. The disadvantage of such an arrangement is the fact, that the sensors should be connected with the recording device. But this problem can nowadays be solved by transmitting the signals via mobile phone connection and synchronisation via global positioning system (GPS) signal. Furthermore if the PD measuring equipment can only be connected at one of the cable termination, the sensitivity depends on the damping of the insulation material and on the length of the cable.

Another diagnostic method is the measurement of the dissipation factor \( \tan \delta \) at low frequency voltage of 0.1 Hz.

The change of the dissipation factor as function of the applied voltage, often mentioned as tip-up dissipation factor, is an indication of the insulation material ageing. Fig. 11 shows examples for a medium voltage cables. As higher the ageing as lower is the voltage where the dissipation factor starts to increase.

The solid insulation is very often assumed as a complex system with a number of different dipoles inside the material which behaves different depending on the ageing. Such a system can be simplified represented by a number of RC circuits as shown in Fig. 12.

The capacitor \( C_0 \) and the resistor \( R_0 \) represent the geometric capacitance and the conducting part of the insulation system. The different RC combinations \( R_1C_1 \) up to \( R_nC_n \) represent the different kind of dipoles generated during by the ageing of the material and influenced by the humidity within the insulation.

To use this model for the evaluation of the ageing status the measurement of the recovery voltage (RVM), the measurement of the polarization (depolarization current (PDC) or the frequency dielectric spectroscopy (FDS) can be used. Also the so called isothermal relaxation current (IRC) measurement is based on the same physical behaviour of the insulation material. Two of these methods, the PDC and FDS, can be applied for the monitoring and diagnosis of solid-liquid insulation systems. Fig. 13 shows the results of an RVM measurement.
The IRC measurement is not as simple because one of the requirements is the same temperature at the measurement in order to evaluate the ageing status. Furthermore the current in the first few seconds is very high due to the discharge of the cable capacitance. Therefore the diagram shows not the current but the product of current multiplied by time which is equivalent to a charge. Fig. 14 shows the measurements of a new cable and two different aged cables.

![Figure 14. IRC measurement on three medium voltage cables](image)

All the methods need unfortunately its reference measurements if not only go – no go information is required.

V. SOLID-LIQUID INSULATION

The combination of solid and liquid insulation systems is typically for power transformers, shunt reactors, instrument transformers, bushings and oil-impregnated cables. The most complex apparatus is a power transformer and therefore the monitoring and diagnosis devices presented here are to be used in this kind of apparatus. An overview of a more or less complete monitoring system is shown in Fig. 15 where the diagnosis is usually implemented in the software.

![Figure 15. Simplified equivalent circuit for aged synthetic material](image)

Besides the common information like temperature, voltage and current the following information are used for diagnosis:

- Dissolved gas-in-oil analysis (DGA)
- PD measurements
- PDC measurements
- Frequency response analysis (FRA)

The DGA is a well known diagnosis method which is based on the different kind of gases dissolved in the fluid and where the amount of gas as well as the relation between some gases provides information on the failure and in some respect ageing of the insulation system [11]. The failure could be thermal overload, discharges within the transformer or PD. The ageing of the paper insulation is represented by the production of CO and CO₂ as well as by the analysis of the Furan content. The common diagram of the failure analysis is the so called Duval Triangle where three main failure gases are evaluated and estimated [12]. Fig. 15 shows the triangle.

![Figure 16. Duval Triangle](image)

The abbreviation in the diagram means D for discharge and T for thermal failure or overload, where the figures 1 to 3 representing the energy of the discharge of the temperature range.

One of the most important information is the condition of the solid insulation, in power transformers paper and transformer board, but these components are not accessible without opening the transformer. Therefore some measures are required to get the information. One method used for a long time is the calculation of the humidity in the paper, one of the parameter which determines the electrical performance. Fig. 17 shows the equilibrium diagram for new mineral oil as insulation fluid.

![Figure 17. Equilibrium state of the water content in paper and oil](image)

It can be clearly realized that the most part of the water is in the solid insulation, that means in the paper, because here the content is given in % and in the oil in pars per million (ppm).
Besides the electrical performance the mechanical strength of the paper is also important because the mechanical stress is very high during a short circuit near the transformer. The Furan analysis gives information about the degree of polymerization (DP) which is a measure for the mechanical strength of the paper. Fig. 18 shows the decrease of the DP value with increasing furan content, where the 2FAL is the most sensitive component.

Figure 18. DP value as function of the 2FAL value

It should be taken into account that different solid or liquid insulation material may lead to different values of the 2FAL and also the humidity has an influence on this value [13]. The dielectric response of a power transformer insulation system is a measure for the condition of the insulation system. The two methods, the PDC and the FDS, gave the same information, but the procedure could be very time consuming in one or the other case depending on the time or the frequency. Fig. 19 and 20 show examples for such a measurement and the interpretation.

Figure 19. PDC measurement at different moisture content

The difference in the relative humidity can be recognized at very long measuring time, and therefore the FDS method is more efficient in this time range or resp. frequency range. The difference in moisture is also shown in Fig. 20 as function of the FDS method. The difference can be recognized at very low frequency which is equivalent to very long measuring time with the PDC method, but the measurement itself can be carried out in a relatively short time. Therefore both methods are combined in order to have an optimum in the duration of the measuring procedure.

The dissipation factor is also a measure for the performance of the insulation system. Fig. 21 shows an example of a measurement

Figure 21. Disipation factor s function of the frequency as measure of the performance of solid - liquid transfoe insulation system

Besides the performance of the insulation system material it is also important to know, if the mechanical performance of the windings is still good. The change in the geometrical arrangement or a short circuit in the winding can be evaluated by the Frequency Response Analysis to a certain extent. This measurement is based on the theory that the transformer is a linear system and the output signal is given by the input signal and signal transformation within the transformer. Fig. 22 shows an example of a measurement. A change in the winding configuration leads to a change in the resonance frequencies and poles and can also changed the amplitude through a damping effect. However research activities are still going on the find out the sensitivity of this method in order to get more precise information up to which mechanical deformation or number of short circuited windings the FRA method will indicate a change and in consequence a defect. This method can also be used to monitor the changes during transportation or some other work on a power transformer.
A further important point is the situation, if PD are recorded but the origin and the location are unknown. The use of the transfer function, divided in so called winding section transfer functions, allows the calculation of the PD location with the help of two measurements, on the bushing and the neutral point of the transformer. Fig. 23 shows the model arrangement in the laboratory and Fig. 24 a measurement on a distribution transformer.

The calculation of the signals shows a good agreement for the origin 3 and this was the position where the PD signal was injected in the investigated transformer.

The main problem within this method is the determination of the winding section transfer function. If these functions can be determined during the manufaturering of the transformer and confirmed during the acceptance tests a very informative fingerprint will be available for the PD measurement offline as well as online.

VI. CONCLUSION

The condition monitoring and diagnosis are tools with an increasing importance due to the age of the existing transformers, the increase of the economical pressure on the utilities and the reduction of the safety margin regarding design and loading.

The available tools are good and should be used in parallel to prevent wrong interpretations based on one kind of measurement.

There is still some research work to do regarding the correlation between the measured parameters and the evaluation of the remaining life time and the relevant risk during this time.

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