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The Impact of Insulation Monitoring and Diagnostics on Reliability and Exploitation of Service Life

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SUMMARY

The progress in automation and information technology has led to substantial improvements of existing and introduction of totally new monitoring and diagnostic systems. Normally those systems are applied for costly pieces of equipment as gas insulated substations (GIS), power transformers and power cable systems. Since the dielectric properties are the main criteria regarding the service performance of this type of equipment, insulation monitoring and diagnostics are considered mainly. The application of those systems is also of special interest with respect to insulation coordination.

Insulation monitoring and diagnostics generally aims at two fields of application, first the detection of incipient faults and secondly exploitation of service life. The detection of incipient faults is mainly of interest to reduce the failure rate furthermore thus decreasing the outage time as far as possible, since a failure during operation in the equipment under consideration mostly causes a longer outage time and considerable cost expenditure for repair and replacement. With this, an improvement of the reliability and availability of the station can be obtained. The exploitation of service life is of interest, since the equipment in question shows a very good long-term performance, the service life often being much longer than expected. By means of insulation monitoring and diagnostics a qualified assessment of the dielectric properties is made possible. In this way a life extension of the equipment is possible and a more intensive exploitation is accomplished leading to considerable savings in investment costs, i. e. reduction of life cycle costs (LCC).

Based on a detailed study of failure rates and service experience investigations are performed how far insulation monitoring and diagnostics can contribute to improve reliability and exploitation of service life of gas insulated substations (GIS), power transformers and power cable systems. The outcome is strongly dependent on the ability of the systems, in particular on the sensitivity to detect critical defects. Therefore the systems available today and the critical defects known from service experience are considered with this respect.

Finally, recommendations are given at which installations and equipment the application of monitoring and diagnostic systems are reasonable and can also be justified from the economical point of view.

KEYWORDS

Insulation co-ordination, diagnostics, gas insulated substations (GIS), life cycle costs (LCC), monitoring, power cable systems, power transformers, reliability, service life

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1. Introduction

The progress in automation and information technology has led to substantial improvements of existing and introduction of totally new monitoring and diagnostic systems. Normally those systems are applied for costly pieces of equipment as power transformers, gas insulated substations (GIS) and power cable systems. Those systems can provide a lot of information of each piece of equipment which can be utilized for maintenance, but also for improvements in availability and exploitation of service life. Furthermore one can make use of this information for system design and system layout.

Since the dielectric properties are the main criteria regarding the service performance of this type of equipment, insulation monitoring and diagnostic systems are mainly considered in this paper. Typical examples of monitoring and diagnostic systems for transformers, GIS and cable systems are given and the impact on reliability and exploitation of service is presented. Finally the benefits for the user are discussed.

2. Modern monitoring and diagnostic systems for power equipment

In the mean time a lot of pieces of equipment fitted with monitoring and diagnostic systems are in operation and rather extensive service experience with these systems could be gained. Partly these systems are applied for surveillance of the service conditions, predominantly of the insulating properties, some of them were mainly installed to obtain a more qualified affirmation of the sound insulation condition during onsite testing.

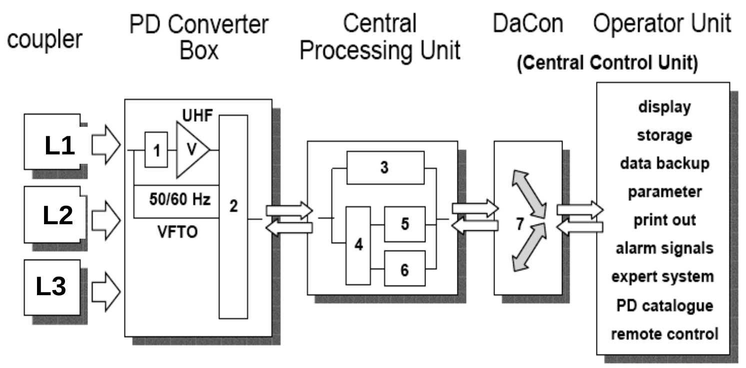
Besides the equipment specific requirements some general requests can be given. Generally a high degree of reliability is necessary. This includes self-checking, monitoring of all sensors connected and a plausibility check of all incoming data as well as sufficient electromagnetic compatibility. In case of an outage of the monitoring system an uninterrupted operation of the primary equipment has to be possible. With integrated systems for monitoring and control one has to provide for a corresponding redundancy or a backup level. The reliability requirements often seem to be crucial due to the high degree of reliability of the of the primary equipment which is monitored. Therefore sensors with standard interfaces have to be installed. The application of replacement type sensors should be possible by a simple exchange procedure. For that, mechanical precautions at the sensor location have to be provided. Furthermore, computer systems with standard interfaces as open systems, i. e. capable for extensions and retrofit, should be applied. Finally, the environmental conditions on-site have to be considered.

2.1 Monitoring and diagnostic systems for GIS

GIS have been in operation for more than 35 years and they have shown a high level of reliability with extremely low failure rates. This is the result of quality assurance during the design and manufacturing process as well as during the erection and on-site commissioning. However, the return of experience shows that some of the in-service failures are related to defects in the insulation system.

Nowadays many of these defects can be detected in service by continuous PD monitoring based on the UHF technique. The UHF signals may readily be picked up by UHF couplers fitted either inside the GIS chambers, or over dielectric apertures in the enclosure [1]. The UHF signals can be displayed in different ways where their characteristic patterns reveal the nature of any defect that might be present in the GIS. The captured pulse sequences are analysed automatically with good accuracy by modern PD monitoring systems and only service relevant PD alarms are submitted to the substation control system. With such an early warning of an impending breakdown, utilities can take appropriate action.

An acoustic PD measurement can be used as a periodic diagnostic tool for gas-insulated insulation systems in service in case that the UHF technique can not be applied. Most of the critical defects can be detected by acoustic PD instruments. The acoustic method becomes more important in future due to the evaluation of the insulation system on older GIS installations [2].



- UHF couplers: Antenna for UHF signals
- PD converter box: Signal conversion from UHF to low frequency, noise rejection
- Central processor unit: Monitoring of data stream
- Data concentrator: Share/fit together of data stream
- Operator unit: Data display, archiving, remote control, identification of PD defect

Fig. 1: *Basic concept of a PDM system*

Modern partial discharge monitoring (PDM) systems consist of standardized electronic boards and commercially available components with high reliability and an expected lifetime of more than 15 years. Different hardware modules can be easily arranged to build up a customized PDM system which enables a sensitive PD monitoring with a detection level of about -75 dBm. The man-machine-interface for manual operation of the system is realized by user-friendly software with flexible PD data display including trend diagrams and customized reporting of the monitoring results. Worldwide remote control of the systems is state-of-the-art. **Fig. 1** shows the basic concept of a PDM system.

2.2 Monitoring and diagnostic systems for power transformers

Modern power transformer monitoring mainly focuses on the supervision of the following diagnostic parameters:

Gas and humidity content of the oil, oil temperature and oil level, temperature of the ambient air and of the cooling medium, service voltage and current, overvoltages, PD as far as measurable, tap changer position, torque movement of the OLTC motor drive etc.. For permanent monitoring the transformer has to be fitted with sensors being able to monitor those quantities chosen as diagnostic indicators [3]. Besides monitoring of the above mentioned quantities those sensors allow further monitoring functionalities with regard to the different components of a transformer as active part, bushings, cooling unit etc.

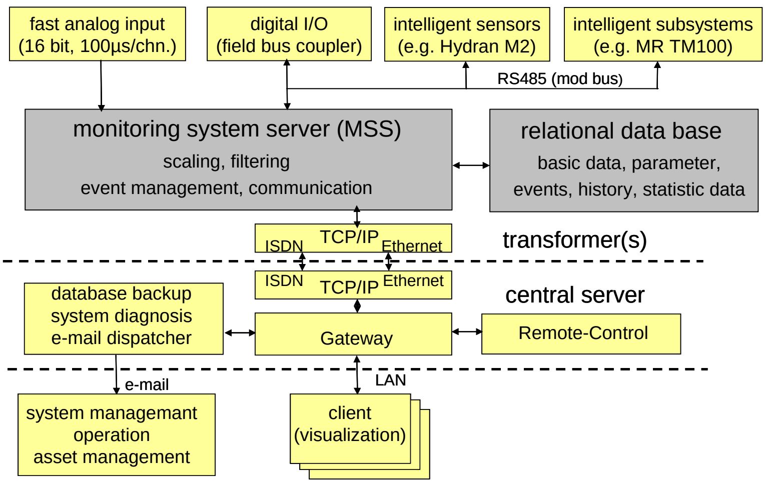


Fig. 2: *Basic concept of an on-line monitoring system for power transformers*

The basic concept of an online monitoring system for power transformers is shown in **Fig. 2**. The system is fitted with analogue, digital and serial interfaces, the latter one based on RS 485 mod bus by which intelligent sensors and subsystems can be connected. The signals generated by the sensors are evaluated in the monitoring system server (MSS) where event management, filtering and scaling as well as the communication with the relational data base is carried out.

All data enter the data base containing an event and short-time storage and a long-term storage. After evaluation and data compressing the data are stored in data archives. The before mentioned system is directly located at the transformer under surveillance. Via an ISDN or Ethernet link it is connected with a central server unit where the diagnosis functions are performed. The outcomes are warnings and information for the system management, the system operation and asset management. The evaluation and visualization is achieved by a standardized software which can also be used for systems of different manufacturers. Via a LAN-connection authorized users have access to the central server.

2.3 Monitoring and diagnostic systems for power cable systems

Cable monitoring is today mostly concentrated on the local temperature distribution and the actual level of any partial discharge (PD) activity in all parts of the cable system. The demand is mainly related to new cable connections with extruded XLPE insulation systems. It is therefore justified to restrict here on HV/EHV cable systems which are covered by IEC 62067.

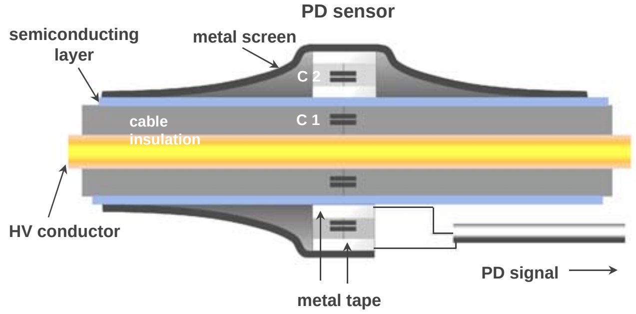


Fig. 3: *PD sensor installed in a cable joint*

XLPE cable insulations are sensitive against temperature stresses exceeding the permitted limits. The risk for such incidents is less a global overload of the cable but much more an inhomogeneous temperature distribution (hot spots) over the cable route. A powerful tool to detect such irregularities is the distributed temperature measurement using the physical backscattering behaviour of optical fibres which are integrated in the cable design.

It is commonly accepted, that the absence of any observable PD is the central quality criterion for XLPE insulated HV/EHV cable systems. On site PD detection and monitoring can focus mainly on the cable accessories as the cables were already routine tested in the factory and the accessories made on site bear the highest risk for laying and installation faults. PD sensors integrated in the cable accessories provide a better way for sensitive PD detection as the detection at the cable ends. Several types of sensors are today available, e.g. capacitive, inductive or directional coupler sensors. An example is given in **Fig. 3**. On long cable systems with cross-bonding (CB), PD detection is also possible by installing inductive sensors in the CB links.

3. Aims of insulation monitoring and diagnostics

Insulation monitoring and diagnostics of HV power equipment generally aims at two fields of application, first detection of incipient faults and secondly exploitation of service life [1].

3.1. Detection of incipient faults

The detection of incipient faults is mainly of interest to reduce the failure rate and to decrease the outage time as far as possible. Since a failure during operation would mostly cause a longer outage time and more cost expenditure. With this, an improvement of the reliability and availability of the equipment and system in total can be obtained, because repair works or exchange measures, if needed, may be initiated before a breakdown or an outage occurs. As a consequence a better utilisation of the equipment and an adoption of maintenance strategies may be achieved by a more qualified knowledge of the insulating condition.

3.2 Exploitation of service life

The exploitation of service life is of interest, since HV power equipment normally shows a very good long-term performance, the service life being much longer than expected when the first installations were taken into service. By means of insulation monitoring and diagnostics a qualified assessment of the dielectric properties of the equipment in question is made possible. If weak points will be detected in future the components in question can be exchanged and the equipment in concern can be operated without any further restrictions. In this way a life extension of the equipment is possible and a more intensive exploitation is accomplished leading to considerable savings in investment costs, i. e. reduction of life cycle costs (LCC).

3.3 Economical Benefits of monitoring and diagnostic systems

In general, the user expects economical benefits by the installation of monitoring and diagnostic systems at which the overall life cycle costs (LCC) are considered.

Table 1: *Impact of monitoring and diagnostic systems on LCC*

CI	**+**
CP	**–**
CR	**–**
CO	**0**
OC	**–**
CD	**0**
RSL	**+**
LCC	**–**

CI investment and installation costs
CP costs for planned maintenance
CR costs for unplanned maintenance and repair
CO ordinary operational costs
OC outage costs
CD costs for disposal
RSL Residual service life
LCC Life cycle costs

A rough estimation given in **Table 1** shows how far the different factors are affected by the application of monitoring and diagnostic systems. Normally the costs for planned maintenance (CP) as well as the costs for unplanned maintenance and repair (CR) and the outage costs (OC) can be reduced. Due to the additional costs for the monitoring system the investment costs (CI) will slightly increase. However, as a result of the information and the knowledge gained the residual lifetime can be assessed in a more qualified way, thus a far extending exploitation of the residual service life (RSL) is possible. In total, considerably lower LCC can be expected.

3.4 Assessment of insulation performance with regard to insulation co-ordination

Insulation co-ordination according to the IEC 60071 standards series addresses two aspects of insulation performance:

- Insulation co-ordination which requires the selection of the insulation such to obtain an acceptable failure rate of the equipment during its service life. This part includes all influences on the insulation performance measures under the voltage and environmental stresses of the system. It ends with the so-called co-ordination withstand voltages which have to be withstood by the equipment during all service conditions ranging from the continuous operating voltage of the power system up to system transients.
- Standardization of withstand voltages to be applied in standardized tests which assures the necessary co-ordination withstand voltages determined in the step above. This part itself, which also includes the standard or rated withstand voltages of the insulation standardized in tables is not part of the insulation co-ordination, but includes the necessary simplifications to finally arrive at standardized equipment.

It is evident that the requirement of an acceptable insulation failure rate can be met by two alternatives. The first alternative is to apply a sufficiently large safety factor to the co-ordination withstand voltages and to specify the resulting rated withstand voltage for the new equipment only. This procedure has been commonly used for equipment for which a remarkable insulation ageing or degradation during service is not expected and for which the applicable safety factor stays within reasonable limits. A typical example for such types of insulation is the external air insulation which shown little ageing effects and for which the performance under service conditions is well known.

For insulation types, however, for which remarkable ageing may exist from the beginning or may arise from certain system events during service, the application of a safety factor to the co-ordination withstand voltages may lead to excessively high rated withstand voltages to be applied for testing the new equipment to assure a sufficient insulation withstand during service life. In some cases the specification of high rated withstand voltages may not even be successful to avoid excessive equipment failures. Furthermore, the high rated values have to be applied to all equipment of one type, although their degree of ageing or degradation may be substantially different dependent on production quality or stress situation in the service conditions. For such equipment alternative measures to assure insulation conditions which guarantee the required low failure rates are more suitable.

The aim of insulation condition monitoring is to detect and to improve equipment for which an inadequate insulation failure has to be assumed. Adequate reactions as maintenance or replacement of the equipment before failure occurrence guarantee the compliance of the equipment failure rates. Insulation monitoring is a suitable alternative to the adoption of high safety factors and high rated withstand voltages of the insulation and is, therefore a fully acceptable procedure to achieve insulation co-ordination.

4. Improvements of reliability and extension of service life by monitoring systems

4.1 Service experience: Failure rates and main failure causes

Since monitoring and diagnostics mainly aim at detection of incipient faults and exploitation of service life, the analysis of the service experience is an important presumption to achieve the improvements expected by the users. In the following the failure rates and main failure causes are analyzed for the power equipment mentioned before – GIS, transformers and cable systems.

<u>GIS</u>

The dielectric failure rates presented in **Fig. 4 a** are taken from different sources. In range 1 (100..200 kV) the failure rate is in good correspondence and amounts to about 0.2 failures per bay year. In range 2 (300…500 kV) the failure rate is significantly higher due to the higher field strength and the deviations are between 0.9…1.9 failures per bay year [4].

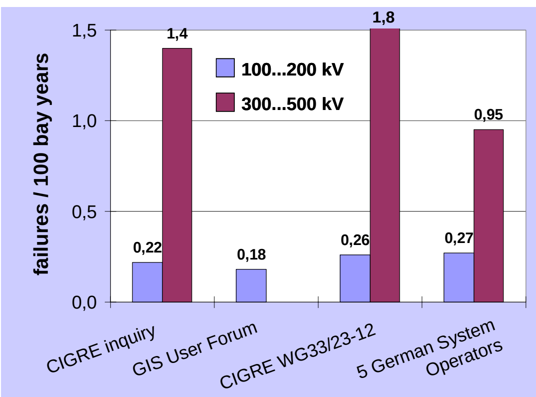


Fig 4 a: *Rates of dielectric failures in GIS*

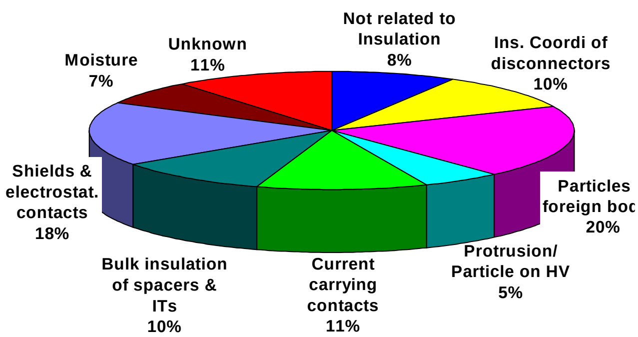


Fig. 4 b: *Main failure causes in GIS*

The main failure causes are given in **Fig. 4 b**. When analyzing the failure causes it has to be stated that a lot of failures do not occur in GIS of modern design, e. g insufficient insulation co-ordination of disconnectors and earthing switches or imperfections in solid material. Furthermore, a reduction of teething faults is likely due to the application of advanced testing methods [5]. Therefore a target failure rate of 0.1 failures per bay year should be achievable, in particular by means of monitoring and diagnostic systems. A sufficient sensitivity presumed**,** nearly 60% of the failures could have been detected by monitoring and diagnostic systems [5].

Transformers

The highest failure rates can be observed at power transformers in the upper voltage levels (**Fig. 5 a**). At this network and generator transformers differ considerably presumably mainly due to the different loading. A generator transformer is normally loaded according to its rated power, whereas a network transformers is loaded to 100 % or more in emergency situations only. Therefore monitoring systems are of particular interest for generator transformers and for network transformers in the upper voltage levels. From **Fig. 5 b** regarding the failure statistics of the defective components it can be derived that besides the active part the bushings and the tap changer should be monitored [6].

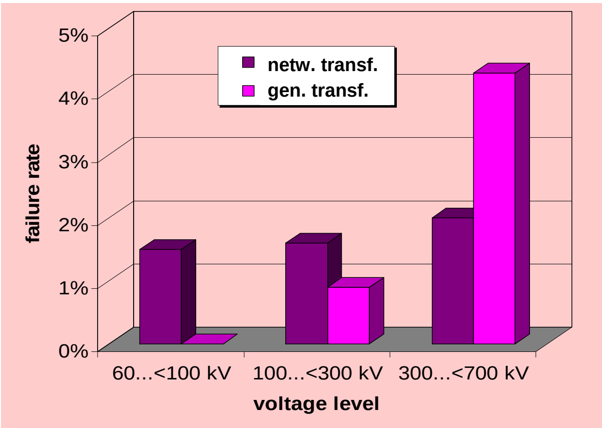


Fig. 5 a: *Failure rates of power transformers*

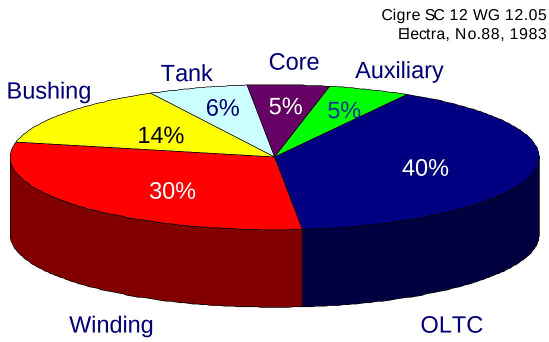


Fig. 5 b: *Defective components of power transformers*

Cable systems

In general, cables represent a reliable component of the power system. **Fig 6 a** shows the overall failure rates of 110 kV and medium voltage cables in Germany, where particularly the high-voltage cables with 0,6 failures per 100 km system length and year show satisfactory performance.

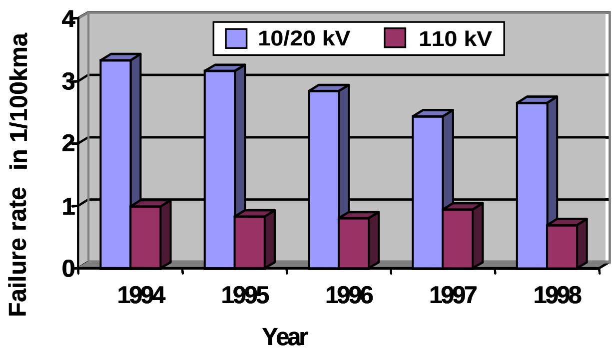


Fig. 6 a: *Failure rates of 110 kV and medium voltage cables recorded in Germany*

Moreover, recent detailed evaluation of nearly 2000 failures in the medium voltage system revealed that the failure occurrence in cable systems remarkably depend on the cable type.

Fig 6 b shows that new XLPE cables produced and tested according to the standard EN HD 620 show an excellent service performance of less than 0,3 insulation failures per year. Main failure reason is dielectric overstress due to lightning.

Papermass cables which have been used from the beginning of cable techniques show slightly higher failure rates than new XLPE cables, but still not a remarkable influence of ageing. Main failure reasons are water ingress due to lead jacket corrosion or mass loss due to untightness of joints.

Contrary to these two cable types older XLPE cables show increased failure rates owing to water treeing. Such cables are nearly exclusively responsible for the high failure rates of medium voltage cables shown in **Fig. 6 a** [7]**.**

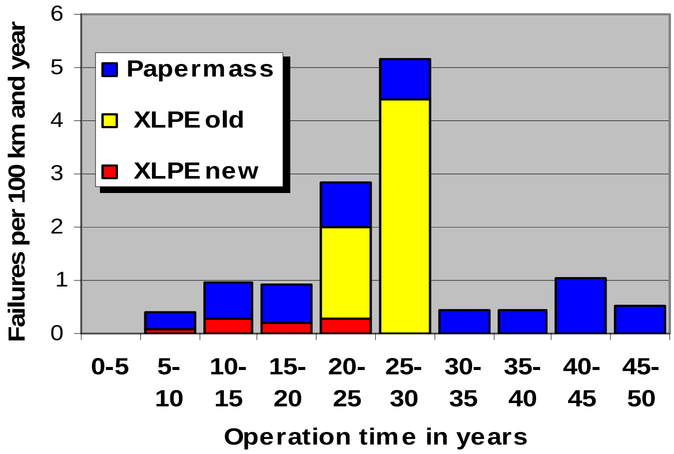


Fig. 6 b: *Failure rates of medium voltage cables depending on operation time observed in Germany*

Modern high-voltage cables have the same construction principles as the new XLPE cables in the medium voltage range. Although exact failure evaluation is not available, failure rates as low as that shown in **Fig. 6 b** for the new XLPE cables can be assumed [8]. Therefore, it is not expected that insulation monitoring of such cables will be required in near future. However, the service performance of terminals and joints is not included in the reported failure rates. The quality of these strongly depends on the mounting quality and monitoring this quality may be a future task [9].

4.2 Ability of actual systems

Based on practical experience with actual monitoring and diagnostic systems it is shown in the following how far these systems are able to improve reliability and exploitation of service life.

4.2.1 GIS

A PDM system normally operates as a “black box”, which captures UHF signals and submits warning and alarm signals to the substation control system only in case of service relevant PD activity. Therefore the most important PDM system features are the applied noise suppression techniques and the efficiency of the PD identification algorithms. Nowadays the suppression of noise and other background signals like radar or mobile phone signals is realized by combined hardware and software filters. Actual PD identification algorithms are based on phase resolved pulse sequence analysis. The applied redundant diagnosis systems (RDS) with hierarchical or hybrid structures consist of PD feature extraction and defect classification in combination with a proper reference data base to identify the type and nature of the insulation defect. The results from such RDS can have an accuracy of correct identification in the range of more than 95 %. Only a very small number of captured PD data sets are classified as unknown defect or identified in a wrong way.

The ability of PDM systems can be described by the successful detection of PD defects during commissioning and operation and the prevention of related breakdowns. A PD detection sensitivity which is equivalent to 5 pC or even better can be obtained by modern PDM systems for any defect position based on a sufficient number of UHF couplers installed at the complete GIS substation. This sensitivity is not sufficient for detection of all critical defects, but a large number can be detected.

Return of experience from GIS operation is available nowadays for the statistical evaluation of online PDM system application. Two different data bases are available [10].

One database covers the experience from monitoring on more than 360 UHF couplers, which are located at six GIS from the same manufacturer with rated voltages from 245 kV to 550 kV. PD data of a seven year period and more than 220 bay-years resp. 1350 UHF coupler-years are available in total. Only one defect was detected during operation. This defect was confirmed by visual inspection and removed during the planned repair work. For all six GIS with PDM application no in-service breakdown occurred. The related PD defect rate can be calculated to 0.45 PD defects per 100 bay-years resp. 0.074 PD defects per 100 UHF coupler-years.

The other data base contains results since 1996. More than 3000 UHF couplers related to different GIS manufacturers and rated voltages from 132 kV to 800 kV are monitored. The results from more than 1000 bay-years of in-service monitoring show that 47 critical defects were removed and breakdown occurred for unknown causes in only two GIS.

4.2.2 Transformers

Fig. 7 shows the visualization of a transformer monitoring system, as it is described in chapter 2.2 belonging to a 400 kV /300 MVA network coupling transformer. The diagnostic quantities gas and humidity content of the oil, oil temperature and oil level, ambient air and cooling medium temperature, service voltage and current, PD if measurable, tap changer position etc. are permanently observed. Additionally different alarm and warning signals are indicated.

Fig. 7: *Visualization of the diagnostic quantities and alarm and warning signals of a transformer monitoring system*

Fig. 8 presents records of the oil temperature, the hydrogen content and the loading taken from a monitoring system of a transformer of the same size which apparently give indication of irregularities in the active part of the apparatus. The transformer was put into operation after repair with a new active part. After commissioning the hydrogen content detected by the on-line monitoring system increased continuously. An increase of oil temperature by special control of the cooling unit revealed that the concentration of hydrogen was only dependent on the oil temperature. A correlation with the load factor k could not be detected.

Therefore, an abnormal condition like partial discharges or hot spots due to load current was not probable. The reason for the generation of hydrogen is due to chemical reactions of the new transformer oil [11]. This behaviour during a transformer's initial operating period has become apparent as on-line monitoring has become common, and it has presumably always occurred. Gas formation is most apparent in highly refined oils, probably because the hydrogen and hydro-carbon radicals there cannot react with any unstable structures, since there are no such structures. Also zinc in the pipes of the cooling unit can cause such an increase of hydrogen. An off-line dissolved gas analysis (DGA) to determine the concentration of the other components dissolved in the oil indicated no further gases than hydrogen. So evaluation of several variables by the monitoring system revealed that the generation of hydrogen is caused by chemical reactions and therefore in this case uncritical.

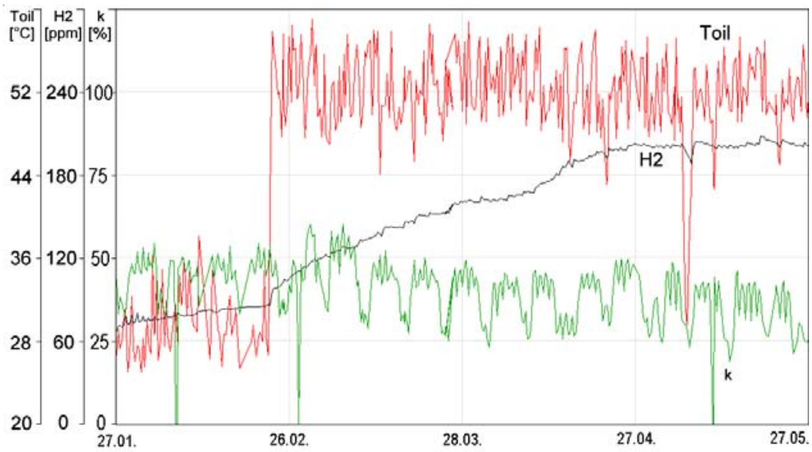


Fig. 8: *Hydrogen content dependent on top oil temperature*

4.2.3 Cable systems

According to section 2.3, PD monitoring depends on PD sensors in cable accessories to achieve maximum sensitivity. To clearly distinguish between internal PD from the cable system and line interference, additional features are required. Best experiences were made with synchronous multi-channel PD measurements [12]. In this case, correlation of time-of-arrivals at each cable accessory is used to identify transition pulses and local PD. Centre frequency and bandwidth can be adjusted by digital filters to obtain best SNR. In cable systems, interference level decreases with increasing cable length between cable termination and cable joint. A cable itself behaves like a low-pass filter, so even at the first joint group PD sensitivities of typically 5pC are achieved. This sensitivity is sufficient for detection of imperfections which will finally lead to a breakdown within the expected lifetime.

After installation tests on a 20km long 400kV XLPE cable system laid in a tunnel (London, Elstree project, June 2005) showed noise levels down to 0.1pC in the middle of the cable. Consequently, cable terminations are the remaining crucial part for online PD monitoring of a cable system. Especially outdoor cable terminations "detect" external interference without any damping. Special solutions exist for GIS cable terminations [13].

5. Economical considerations and recommendations for application of monitoring systems

Cost benefits of on-line monitoring system can be achieved by several items:

- Detection of incipient faults and prevention of downtimes
- Extension of service lifetime
- Use of condition-based maintenance instead of time-based maintenance
- Higher overload capacity of transformers and cable systems
- Avoidance of collateral damages

The calculation of the benefits requires hypothesis of many individual parameters which are difficult to assess. For a general approach not all of these items can be calculated exactly or taken into account. Therefore some examples are given in the following:

Detection of incipient faults in a GIS and prevention of downtimes:

Online monitoring may enable preventive failure detection and decrease the risk of major failures. Furthermore planning of maintenance or repair work is possible to minimize the outage time of the GIS. The economic aspects of insulation monitoring and diagnostics like investment cost and maintenance or repair cost influence the LCC of a GIS.

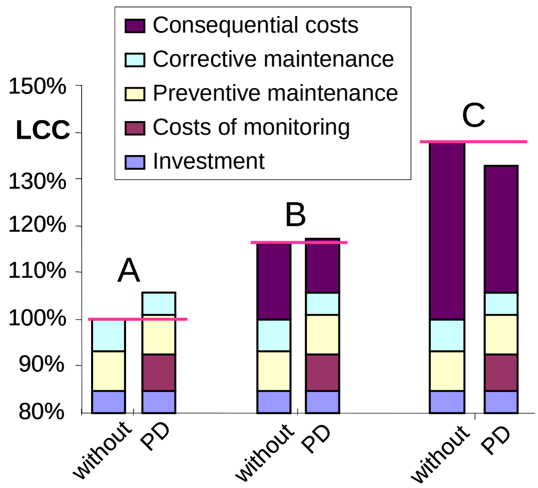


Fig. 9: *LCC for a 420 kV GIS with additional online UHF PD monitoring system*

A *LCC without consequential costs*
B *LCC including costs for loss of income*
C *LCC including costs for loss of income and contract penalty*

For the LCC analysis a 420 kV GIS with an additional online PDM system shall be used as an example [14]. The input data for this LCC calculation are based on Cigrè information (e.g. failure rate, mean time to repair) and assumptions for the consequential cost (e.g. loss of income, contract penalty cost). Especially in case of extremely high consequential cost the LCC of the 420 kV GIS can be reduced by an online PDM system (**Fig.8**). This result is obtained taking into account the general reliability data published by Cigré.

In comparison with these results the application of an online PDM system for a 145 kV GIS makes no sense from the economical point of view, because the LCC analysis shows no benefit even for the worst case scenario with extremely high consequential cost. However, insulation monitoring by periodic checks may be interesting.

Most of the input data for a LCC analysis are based on individual return of experience and knowledge (e.g. type-related failure rates). They should be taken into account to get reasonable results from the LCC calculation.

Extension of service lifetime of a transformer:

By the exact knowledge of the condition and therefore the failure risk the utilization period of the transformer can be extended without having the risk of a sudden death which is especially important for transformers at strategic important locations. Also the knowledge of transformers life is a valuable information to decide which transformer out of a whole population should be scrapped. The savings S gained by a 3 year extension of service life of a 300 MVA transformer can be calculated by assuming a replacement value of 2 M€ and an interest rate of 5 % per annum as:

S (service life extension) = 1.05^{3y} x 2 M€ - 2 M€ = 315 k€

The savings have to be compared with the extra costs for the installation of a monitoring system. The average service life of the monitoring system is expected to be 10 years. Assuming costs for a monitoring system of about 50,000 € means yearly costs of 5,000 €.

From the considerations above one can derive that the application of monitoring systems for GIS and transformers is of special interest with regard to extension of service life and prevention of major failures. Therefore a monitoring installation should particularly be regarded in case of pieces of equipment with high investment cost and strategic importance. Furthermore the advantage of a monitoring system is its inherit ability to give an accurate picture of the operating condition of the transformer, allowing the operator to detect the early signs of faults and correct them. It also provides the tools, in the form of data, to plan maintenance on the basis of the actual condition of the transformer and avoid unnecessary maintenance work.

Monitoring of the dielectric condition of the insulation system of XLPE insulated HV/EHV cables is today limited to a partial discharge detection with a sensitivity as high as technically realisable. As explained above and due to principally unsolved questions regarding interpretation of measured PD characteristics PD monitoring on cable systems can actually not generally be recommended. However, the developments regarding measurement and data acquisition/processing techniques in the last decade, the experience of PD detection during commissioning tests and first trials in living systems have demonstrated that PD monitoring systems are technically available today when needed e.g. for strategic cable systems.

6. Conclusions

In the mean time a lot of costly pieces of power equipment are fitted with monitoring systems. These systems are predominantly applied for surveillance of insulation properties. They mainly aim at detection of incipient faults and of exploitation of service life. With regard to insulation co-ordination insulation monitoring is an alternative to the adoption of high safety factors and high rated withstand voltages to obtain the target failure rates. By the application of monitoring systems the users expect improvements in reliability and better exploitation of service life. As it can be taken from service experience, in particular from considerations of failure rates and failure causes, a distinct portion of failures can be detected. At GIS it is assumed that about 60% of all failures, mainly caused by particles, but partly also by loosed shields or electrostatic contacts or by imperfection in the solid material can be detected. In power transformers beside the active part bushings and the tap changer should be monitored. Insulation monitoring of modern power cable systems is mainly of interest with respect to the performance of terminals and joints. The ability of actual monitoring systems can be described by the successful detection of defects. The return of experience with GIS PDM demonstrate a high detection rate which enables a removal during planned repair work. By means of transformer monitoring systems the diagnostic quantities gas and humidity content of the oil, oil temperature and oil level, ambient air and cooling medium temperature, service voltage and current, PD if measurable, tap changer position etc. are monitored. If indications of irregularities are given, these can permanently be observed and the decision for costly repair work will be taken after through interpretation of the monitoring results. Monitoring systems for power cable systems are up to now mainly applied for commissioning. By multi channel PD measurements a high degree of sensitivity can be obtained which allows the detection even of small imperfections especially in the cable terminations. It can be expected that these systems will also be installed for monitoring during service in future, in particular for strategic cable systems. The cost benefits of monitoring systems with regard to LCC and exploitation could be proven by practical examples. Therefore the installation of monitoring systems can be recommended for costly pieces of equipment and strategic installations.

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