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**INSTRUMENTATION AND MEASUREMENTS
FOR IN-SERVICE MONITORING OF
HIGH VOLTAGE INSULATION**

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Working Group D1.02
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1. Introduction

In-Service Monitoring of high voltage power apparatus is getting a growing interest. Electric Utility companies are operating equipment which has been in service for many years and are now coming to their estimated life time. However it may be economically attractive to operate the equipment beyond this time if the risks of failures and power outages can be minimised. The fully interactive intelligent electricity network requires sophisticated control and communication systems, enhancing reliability and minimising risks of major disruptions. To achieve these goals, sensors and monitoring systems are needed in the front end of the power apparatus, which supply continuous data for the status evaluation of the insulation.

Foremost among the above listed reasons in In-Service Monitoring the following expectations are mentioned:

- Extend the economic life time of equipment and avoid premature retirements.
- Increase the equipment capacity, especially in transmission networks.
- Move from time based to condition based maintenance.
- Extend the operation intervals, reduce maintenance costs.
- Prevent damages, decrease unplanned outages.
- Enhance the availability and reliability of equipment.
- Detect defects before breakdown by warning and alarm functions.
- Improve safety of service personnel.
- Reduce environmental risks.

The order of priorities is changing from user to user. The technical and economical aspects are partly contradictory. A compromise between cost savings, risk reduction and technical performance improvement has to be found.

A major part of all failures in high voltage equipment can be attributed to the insulation system. These failures will normally develop over time, due to the ageing process during the service life or due to local degradation in the material. In order to detect these changes at an early stage, detailed information on the actual insulation condition is necessary. With suitable sensors this information can be derived by monitoring certain parameters during the operating of the equipment. Such parameters can be for example partial discharge impulses, leakage currents or gases in oil. The term 'In-Service Monitoring' is used for such methods during the time when the operating voltage is switched on. In contrast the terms 'off-line' or 'on-site monitoring' are also used for methods during the operating voltage can be switched off and other test voltages are applied.

This paper summarises the work performed by Task Force 08 of Working Group D1.33: 'High Voltage Test and Measuring Technique' and presents an overview of today applied methods for In-Service Monitoring and conclusions regarding the state of the knowledge on the applicability.

2. General Structure of In-Service Monitoring Systems

Depending on the type of equipment and the objectives, monitoring systems can have very different physical realisations. In most cases the systems are based on a common structure, presented in figure 1.

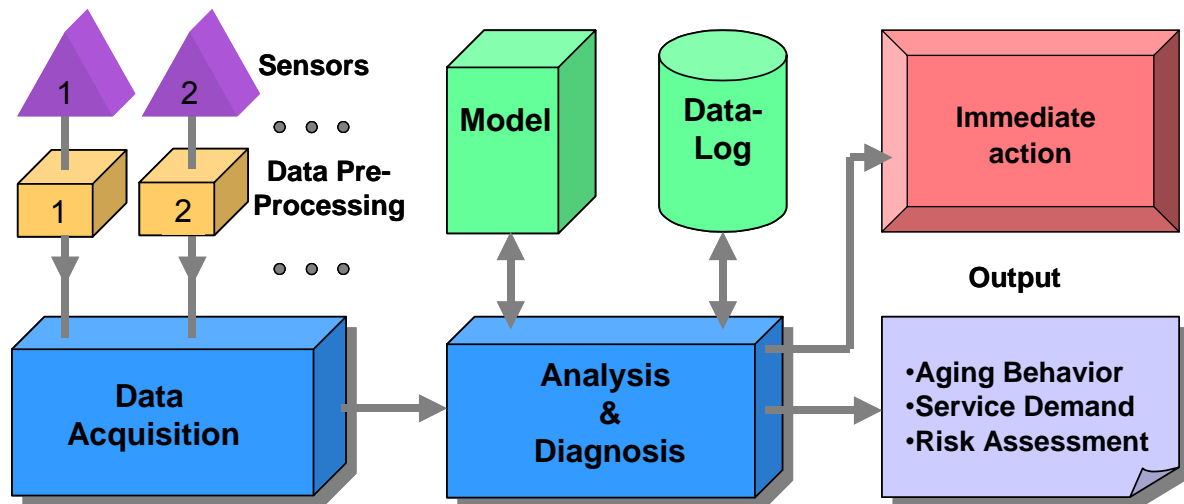


Figure 1 General Structure of an In-Service Monitoring System

The input signals are originating from different sensors in or near the high voltage insulation which are connected to a measuring unit. From this measuring system or platform the data is sent to an acquisition unit. Depending on the surrounding and type of signal, the measuring unit can be located directly at the sensor or the signal is transmitted in an appropriate way to a central processing device. The common trend is the direct pre-processing of the signal near the sensor. The data is then sent digitally to the data acquisition unit. The time intervals between measurements are depending on the method, they can be in the range of microseconds to seconds or minutes. Also, the dynamic range and the signal to noise ratio is depending on the task and will vary in a wide range.

Following the acquisition the signals are analysed. In contrast to pure measuring systems which display values or curves of the measured signal, a monitoring system has to evaluate and process the input signals which can be in ASCII or binary code. This analysis is normally supported by the data log (for instance a SQL server) and a suitable model of the investigated equipment. The data log provides a history file of measurements, giving access to former status and time dependent changes in the insulation. On the other side a model of the apparatus interprets and extrapolates the data. This could be for example the simulation of the degradation process or the calculation of partial discharge development.

The analysis unit can be a single local processor or can be part of a network. The actual measurements together with the former history and the simulation reveal the actual status of the insulation. Only the necessary output of the system is then brought to the operator by a suitable communication method, e.g. Internet, SMS, service call, alarm message. If necessary and urgent, an immediate action is triggered, e.g. switching of the circuit breaker, taking the equipment out of service.

3. Measurement Instrumentation & Methods of HV-Insulation Monitoring

Depending on the different apparatus and different insulation materials a great variety of instruments and methods for monitoring can be found. The following table gives a very general overview for the different equipment and methods that are used today. It shows that partial discharge and temperature monitoring together with gas analysis are more or less widely accepted in-service methods for insulation monitoring. Especially the In-Service Monitoring of high voltage generators, transformers and cable accessories is meanwhile on the way to common practice. For detailed information the responsible committees have published technical brochures which can be found in the references [1-4].

Monitoring Method Type of Equipment	Partial Discharge PD	Gas Analysis DGA	Leakage Current	Transfer Function TF	C / tan δ	Polarization Methods	Temperature
Rotating Machinery							
Motors	•					•	•••
Generators	•••	•	•			•	•••
Substations							
Transformer Winding	•••			••		•••	••
Transformer Oil		•••					•••
Bushings	•		•		•		
Arresters			••	X			•
Switch Gear	••	•		X			
GIS	••	••		X			
Instrument Transformers	•	•	•	•	•	•	
Capacitors	•				•		
Transmission Lines							
Insulators		X	•	X			
Cable Insulation	•	X	X	X			•••
Accessories	••			X			•
Gas Insulated Lines GIL	••	••	X	X			

Table 1 Primarily Applied Methods for In-Service Monitoring of HV-Insulation.

- : many working systems, generally accepted
- : some working systems, accepted by different users
- : small number of working systems, methods under consideration
- x : not applicable

Figure 2 and 3 are showing an example of a PD In-Service Monitoring system with on site data processing and remote on line diagnosis.

4. In-Service Measurements in Relation to Factory and On-Site Tests and Measurements

The expectations and the aim of In-Service Monitoring are based on other tests and measurements during the life cycle of an insulation (table 2). Before the relation between both will be investigated, the characteristics of tests and measurements shall be classified.

The condition of an insulation can be characterised on the one hand by integral measurands related to the overall degradation process (e. g. loss factor, recovery voltage, absorption currents), on the other hand by weak point - related test and measuring results (e. g. withstand voltage, partial discharges, transfer functions). It has to be stressed that the failure of an insulation, - the disruptive discharge -, is always a weak point phenomena. The weak

point might be the result of a failure in production, on-site assembling or – after years of service – the mentioned long-term degradation process [8]. Therefore a weak point related test or measurement delivers a better estimation for the total failure (breakdown) of the insulation and its life expectation than an integral measurement.

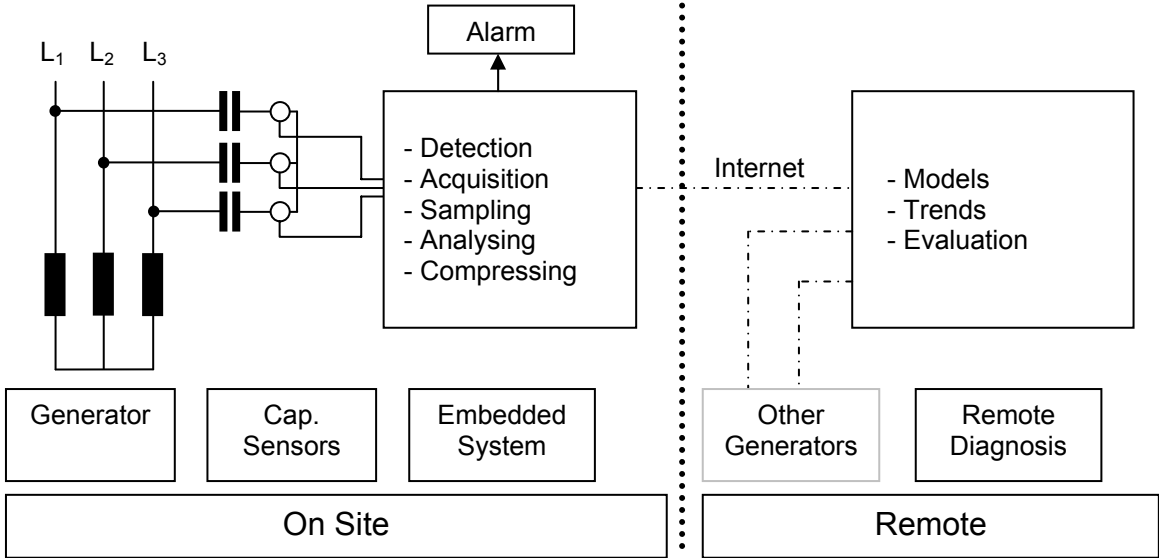


Figure 2 PD In-Service Monitoring System

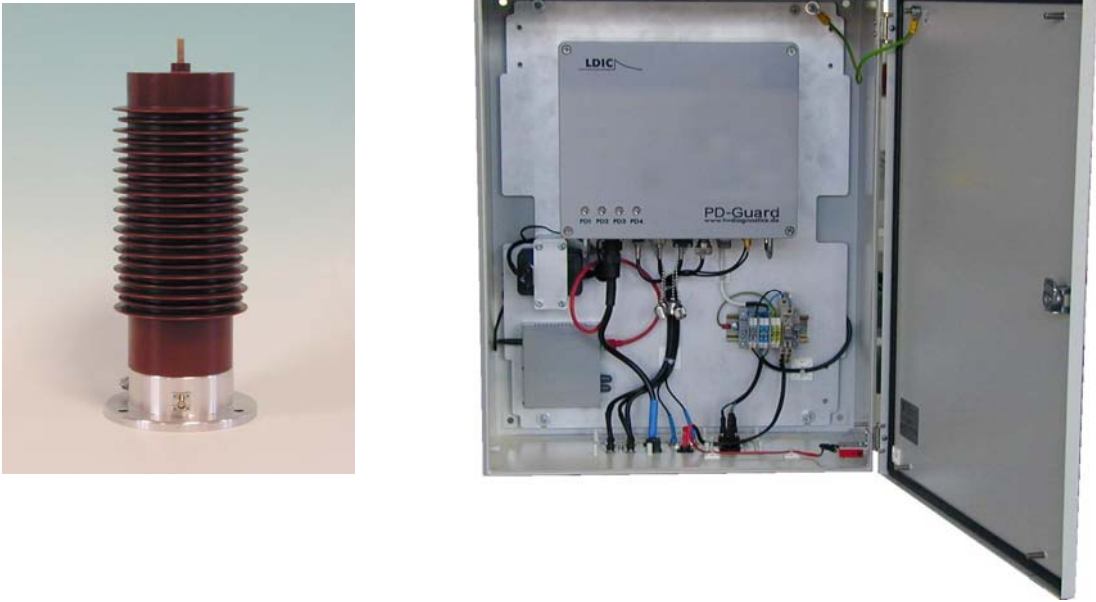


Figure 3: PD Coupling Sensor for generator monitoring (left) and On-Site Measuring unit (right)

Responsibility	Phase	Tests and Measurement	Data
Manufacturer	research	breakdown tests and measurement of material characteristics (PD, tanδ...etc)	basic material data short and long term limits
	development	type tests to demonstrate the correct design	general basic data of the type
	production	routine tests to demonstrate the correct manufacturing	basic data of the apparatus, statistical evaluations
	transportation, assembling on site, commissioning	on-site & off-line test to demonstrate correct condition for service	basic data of the apparatus under on-site condition
User	service (maintenance)	In-Service Monitoring and diagnostic evaluation	monitoring data and diagnostic conclusion ↓ WARNING and recommendation for maintenance
	serious warning of the monitoring system	on-site / off-line test to clarify the condition	test data and conclusion for repair
	repair re-commissioning	on-site / off-line test to demonstrate correct condition for service	updated data for on-site condition
	condition based service, maintenance and repair	This cycle might be repeated several times until the end of utilisation (life cycle)	

Table 2 Data on the insulation of a HV apparatus during its life cycle

For detection of dangerous weak points a withstand voltage test gives a very clear indication by failing the test. Therefore it is a direct test with a clear result. For service-aged insulation a withstand test may cause an accelerated degradation. A PD test result characterises also a weak point, but normally gives no clear indication for its risk of a total failure (breakdown). Therefore, a PD test has to be classified as an indirect test.

The risk of the accelerated degradation of the insulation and the following earlier failure in service by a “direct” withstand test is avoided by the combination with “indirect” tests before and after the withstand test. Depending on the apparatus, such indirect tests can be for example PD tests at cables or transfer function comparison at transformers. Such a combined test is nowadays the best available test procedure for weak point detection in both, new and service-aged insulations. The decades of experience of these test procedures can deliver the basis for the interpretation of In-Service Monitoring [6]. Moreover, the routine and on-site tests should be connected with first fingerprint measurements on the initial status of the insulation, performed with the monitoring system.

Over the service time, In-Service Monitoring reveals deviations from the initial status. For this purpose models of the normal ageing processes must be implemented in the simulation model. Trends of accelerated ageing or abnormal trends can be found by comparing actual measurements with laboratory and simulation data. Alternatively to a model some monitoring systems use ‘experience curves’ of normal aged equipment. If the analysis reveals a dangerous status, warnings and actions can be taken immediately, minimising the risk of outages and reducing the costs of regular inspections and maintenance.

A clear decision after the warning by In-Service Monitoring might be quite difficult, depending on the values of the monitored equipment, its strategic importance and locality in the power system, the uncertainty of the diagnostic result, etc. In such cases an additional off-line test can be performed to analyse in detail the status of the insulation, e. g. by a combined withstand and PD test as described above [4]. One advantage of off-line diagnostics is, that different voltage levels can be applied, e. g. PD inception and PD extinction voltages can be measured. A more reliable classification of the investigated equipment into “safe for service”, “conditional safe” (further observation by enhanced monitoring) and “critical for service” (repair or replacement) can be performed. Used in that way, In-Service Monitoring and on-site / off-line testing are methods which complete each other.

5. Impact on System Development

The conditions for monitoring equipment on-site are substantially different to test laboratories or other in-house measuring systems. This has to be taken into account in the development. Special attention should be taken on:

- earthing conditions (voltage rise, stray voltages)
- supply voltages (stability, interference)
- electric and magnetic interference (‘continuous’ and ‘transient’ noise)
- environmental conditions (temperature, vibration, humidity...)
- transmission system (radio link, modem, GMS)

The levels of electromagnetic interference near or inside high voltage equipment are by far exceeding the limits given in existing EMC standards [7]. General guidelines for In-Service Monitoring Systems are under investigation by Working Group D1.33.

Also the calibration and maintenance of In Service equipment needs care. The measurement sensors and recording devices which can be in operation for many years without interruption. should work stable and without substantial maintenance. It is also important that a defect of the monitoring system must not disturb the operation of the high voltage equipment in any way.

Another serious problem arises in the maintenance of the monitoring equipment, especially for the availability of electronic components. Regarding the life cycle of modern high voltage equipment the In-Service Monitoring system should have at least the same life time. But it is impossible to design nowadays computer controlled measurement equipment in a way that hard- and software will survive the next 40 years. Spare parts and software service will not be available for that time. The only way out of the problem is to design open systems which use standard interfaces and hard- and software which can be substituted and upgraded.

5.1 Interference

In-Service Monitoring system must operate continuously without any outages in very severe conditions of electromagnetic environment e.g. in power plants or substations.

A monitoring system of a large power transformer for example can consist of several sensors placed on the transformer body with signal cables routed to the place of the acquisition unit normally including a processor or an industrial PC. The cabling of the monitoring system creates large antennas, which form some kind of collector of disturbances which are transferred to the acquisition unit.

Experience shows that the most severe interferences in substations origin from near lightning strokes and from switching of near HV and UHV dis-connectors. In such cases voltages induced into unscreened or bad screened wires can be in the magnitude of kilovolts with a

frequency range of up to tens of MHz. That is why the systems have to be designed with high safety margins of immunity.

5.2 Sensors and Signal Transmission System

One of the crucial points for In-Service Monitoring systems has appeared to be the transmission of the measurement data from the sensor to the data acquisition system. The electrodes of the sensors, which remain unscreened in operation, must be protected e.g. by fast varistors. All cables between sensors and acquisition unit are either twisted well screened wire pairs or coaxial cables, preferably double shielded. Cables should be inserted into bonded metal conduits. In many cases fibre optics can be used for transmission of measuring signals from sensors to the acquisition unit, with no influence of disturbances. However the sensitivity of the optic converter chip in the receiving end of the optic cable can be a source of interference.

5.3 Supply Voltage

In many cases a monitoring system uses the present on-site supply voltage of a substation. The voltage quality cannot be compared with home or office supply voltages. Some measures against heavy disturbances on the power line like transients, harmonics and temporary over-voltages have to be taken. In many cases a redundant supply is needed in case of outages. Some monitoring systems are operating in environments where no supply is present. Besides pure battery powered systems, which always need some maintenance demand, more and more hybrid systems with photovoltaic elements, wind generators and fuel cells are realised.

5.4 Environmental Conditions

The environmental conditions can be quite severe for the electronics. But also the measurement itself can be disturbed by harsh weather conditions. For instance leakage current measurements on insulators are difficult to use in areas with ice and snow. In many cases the monitoring system cannot be placed in substation buildings or similar housings and is subjected to environmental stresses. Cold, wet, rain, heat, sun and their influences can be minimised by suitable placing and design of the cabinet. The experience with monitoring equipment in operation shows, that these conditions often have been underestimated. Measures like ventilation cooling of the housings against sun heating during the day and internal heating against condensing moisture due to temperature differences between day and night are often neglected for on-site equipment.

5.5 Earthing Conditions and EMC

The most sensitive part of the monitoring system is the measuring acquisition unit, which often is placed near the monitored HV insulation due to reasonable short length of sensor cabling. The EMC zone-concept of protection should be followed. The acquisition unit is placed inside a cabinet with defined zones of protection and metal enclosure with only small electrical openings and slots. All signal conductors coming from sensors and entering the protected zone should be connected to conditioning circuits and isolating amplifiers. Isolating amplifiers prevent the computer from galvanic or capacitive coupling to external signal conductors. Power supply cables line should be decoupled, filtered and equipped with over-voltage protection.

5.6 Hardware Reset

Besides above described hardware hardening measures, a digital system must be able to perform an automatic reset after disturbances, black-outs or similar events. Watch dog systems installed on processor cards can be used, combined with devices for second level

hardware reset initiated by a mechanism independent on the state of the computer, e.g. regularly midnight or remote triggered reset.

5.7 Analysis, Evaluation and Results

Supervisory control centres should only receive the really necessary output of the monitoring-system, as mentioned before. Therefore the analysis of the incoming data, along with suitable compression methods and the evaluation has to be done with on-site resources, thus enabling only small data packages, e.g. alarms and warnings to be transmitted to the control centre, operator or whatever next hierarchical level of the network. This philosophy of de-centralised hard- and software in the substation disburdens the control centre and transmission channels, increasing the reliability and availability of the supervisory control in contingency situations.

6. Concluding Remarks

- In-Service Monitoring of high voltage insulation is getting a growing interest for various technical and commercial reasons.
- The first commercial built systems are on the market and in service, up to now most of them are measuring single parameters with threshold warnings.
- In-Service Monitoring demands information from development and initial laboratory tests. Off Line measurements and tests accomplish and complete the analysis.
- In-Service Monitoring equipment needs careful design due to harsh environmental conditions.
- Special Regard and more work should be taken to the calibration of sensors and systems.
- In-Service Monitoring systems should deliver only the necessary output, data analysis and evaluation procedures should be included in the on-site system.
- To achieve the goals of monitoring it needs more understanding of the degradation processes in the insulation. Also more data and experience from equipment in the field have to be collected.

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