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PS 3: Network planning in the context of an ageing transformer fleet

On-Line Monitoring of Electrical Apparatus in Large Power Plants

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SUMMARY

This paper describes general design considerations, the system layout and practical experiences with on-line monitoring of electrical apparatus in large thermal power plants. The availability of electrical equipment in power plants is of utmost importance, since outages can easily lead to financial loss of millions of Euros, even per day. Therefore operators of power plants pay large attention to the system health of their apparatus, particularly these in the functional chain of power generation, as e.g. generators and generator step-up transformers. On-line monitoring appears to be an important tool to provide reliable status information, detect failures early and utilize the full life time.

For identifying possibly unreliable components, general failure statistics provide first input. For example in the work of Cigré WG A2.37 "Transformer Reliability Survey", most failures have been attributed to the dielectric of power transformers. The same failure mode applies for generators. Experiences with specific grid conditions and particular apparatus designs are another input for selecting appropriate monitoring systems. Finally, economic calculations prescribe the frame of the extent of the applied technology.

For large turbo generators, it was decided to monitor the temperature in the slots of the stator and the partial discharges of the stator. The measurement of partial discharges is carried out in a frequency range of several 100 kHz to a few MHz for being more sensitive towards signals coming from the inside of the stator windings. Rotating electrical machines generally have several sources of PD, therefore source separation is essential to discriminate between noise, PD with low failure probability and dangerous PD. In the context of this work, amplitude-based impulse correlations were most effective (3 phase amplitude relationship diagram - 3PARD). Alarms are based on levels as well as on rate of change. PD pattern classification is applied for a basic risk assessment.

For the large generator step-up transformers it was decided to monitor temperatures, dissolved failure gases in oil (DGA), bushing capacitance and dissipation factor, partial discharges and transient over-voltages. Transient over-voltages where suspect to be the reason for a number of breakdowns in the last decades, so their monitoring with true waveform recording was of high importance. Actual measurements show the interaction between the transformer and the grid. For monitoring partial discharges, the traditional measurement of electrical PD pulses at the bushing taps is combined with UHF measurements using drain valve sensors. This is necessary for discriminating between internal, potentially dangerous PD and external corona. For determining the state and ageing condition of the bushings, different methods are used in comparison: sum of current vectors, bushing-to-bushing comparison and the VT reference method. Highest overall system accuracy was achieved with the VT reference method, i.e. ± 2 pF for capacitance and ± 0.5 % for dissipation factor. All measurement functions are illustrated with practical experiences and case studies which help to prove the benefit of monitoring of electrical apparatus in large power plants.

KEYWORDS

Power Plant, Generator, Power Transformer, Monitoring, Insulation, Oil, DGA, Partial Discharge, IEC60270, Bushings

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1 CONDITION MONITORING AND DIAGNOSTICS IN THE CONTEXT OF ENERGY PRODUCTION

The availability of electrical equipment in power plants is of utmost importance, where outages can easily lead to financial loss of millions of Euros. Therefore operators of power plants pay large attention to the system health of their apparatus, particularly these in the functional chain of power generation, as e.g. generators and generator step-up transformers. In this application scenario, condition monitoring and diagnostics promises to provide reliable status information, detect failures early and utilize the full life time of equipment.

For many decades, power equipment users have sought ways to assess the general condition and identify specific problems of their assets. Conclusively, diagnostic tests have been developed, which are applied in the de-energized status. In the last years, a sophisticated means has evolved for collecting a great deal of diagnostic information while the equipment is in service. While periodic off-line diagnostic tests still play the dominating role in condition assessment, “continuous” or “on- line” monitoring promise to have the potential to overcome some of the fundamental limitations of off-line tests:

- Continuous measurement for having reliable measurement data, reducing the effect of "outliers" and for continuous observation of the equipment's condition;
- Early diagnosis of initiating failures for scheduling maintenance actions, therewith supporting condition based maintenance schemes;
- Knowledge of the equipment's historical use for fully utilizing the life span in the context of asset life management.
- On-line monitoring is apparently becoming an essential feature of the "smart" electric utility systems of the future.

The context of large power plants requires specific features of instruments used for condition monitoring and diagnostics:

- Extreme reliability to really help increasing the availability of the likewise reliable HV apparatus.
- The question "How to get real value from continuous on-line monitoring systems?" [1] indeed needs an answer. The integration of monitoring results into existing SCADA systems requires a high abstraction level and sophisticated analysis algorithms.
- Outages need to be avoided. Therefore not only a warning system, but also diagnostic functions are required.

A general first step into condition monitoring is a strategic look into failure statistics for identifying possibly unreliable components. For example in the work of Cigré WG A2.37 "Transformer Reliability Survey", most failures have been attributed to the dielectric of power transformers. The same failure mode applies for generators [2]. Based on this, monitoring of the dielectric integrity seems to be of highest importance. Experiences with specific grid conditions and particular apparatus designs are another input for selecting appropriate monitoring systems. Finally, economic calculations prescribe the frame of the extent of the applied technology.

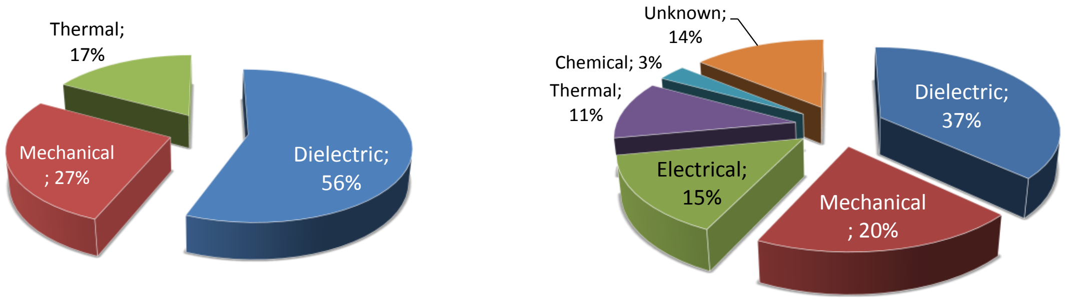


Figure 1 Root causes for failures in hydro generators, [2] (left) and root causes for failures in power transformers after preliminary results of Cigré WG A2.37 (right)

2 CONDITION MONITORING OF LARGE TURBO GENERATORS

2.1 Generator Tests during Outages

Maintenance, inspection and the majority of tests of large hydrogen cooled turbo-generators is only possible within planned outages of the power plant and is subject to significant cost pressure that have resulted in decisions to reduce maintenance and inspection frequency and accept greater operating risk. This trend can be observed world-wide [3]. In the context of this work, the electrical tests as displayed in Table 1 are applied during scheduled outages. Of these diagnostic tests, the authors have found particularly the insulation resistance and partial discharge test to be of highest use.

Table 1: Diagnostic tests for large hydrogen-cooled turbo generators during outages

Component	Diagnostic Test	Frequency
Stator winding	Insulation resistance, polarization index	4 years
	Dissipation factor, tangent delta	4 years
	Winding resistance	4 years
	Partial discharges	4 years
Current Transformers	Electrical and ratio tests?	2 years
Rotor	Insulation resistance, polarization index	2 years
	Winding resistance, winding impedance	4 years
	Winding short circuit test	4 years
Neutral point grounding system	Resistance or impedance measurement	2 years
Generator electrical protection system	Trip and circuit checks, relay injection	2 years

2.2 Generator On-line Monitoring

In-service diagnostic tests can access the generator integrity under real service conditions and allow for planning outages on a long term, if necessary. Table 2 lists in-service or on-line applied tests in the context of this work.

Table 2: Diagnostic measurements for large hydrogen-cooled turbo generators during operation (on-line monitoring)

Component	Monitored Parameter
Stator winding	Partial discharge monitoring Slot temperature monitoring
Rotor bearings	Vibration monitoring
Cooling system	Hydrogen dew-point and hydrogen purity monitoring

2.3 Experiences with Partial Discharge Monitoring

Based on a number of failure statistics [2], partial discharges are a dominant root cause for insulation breakdowns; therefore their continuous observation received high priority. Partial discharges result from stress of the insulation as caused by temperature cycles, the applied electrical stress, aggressive chemical substances, moisture, contamination and mechanical forces. The stator insulation of rotating machines generally exhibits a number of sources of partial discharges, there is no PD-free stator insulation. The fundamental challenge of on-line monitoring is to discriminate between discharges with high, medium and low risk and external disturbances.

During in-service monitoring of partial discharges, a number of these PD sources will be active at the same time. In Figure 2 these are exemplarily disturbances without any relevance for the insulation condition, end-winding surface discharges with medium risk and delamination of tape layers with high risk. As these single sources cannot be measured separately, their specific PD patterns are shown superimposed in a PRPD diagram. The apparent charge is then a result of the superposition of all PD sources. An alarm based on such superposition of different PD sources will not be able to separate the critical source, but may lead to false positives.

To separate between various PD sources, synchronous multi-channel measurement is applied [5]. In the context of this work, three coupling capacitors of 1.1 nF each are mounted into the generator busbar. The 3PARD (star diagram) visualizes the relation among amplitudes of a single PD pulse in one phase and its crosstalk generated signals in the other two phases. By repetition of this procedure for a large number of PD pulses, PD sources within the test object as well as outer noise appear as clearly distinguishable clusters of dots in a 3PARD diagram. Therefore, the 3PARD diagram shows different pulse-type sources in separable clusters. Each cluster can be selected individually and the pattern displayed in a PRPD. No other source is included in the pattern. Figure 3 illustrates the PD source separation by the 3PARD principle as well as the back-transformation of individual clusters into the PRPD representation. In the context of this work, PD expert analysis is performed in the frequency of 1 month. New clusters are separated and individually evaluated via remote access to the monitoring system. Automatic PD source separation and pattern classification is the next step of on-line PD monitoring, [4].

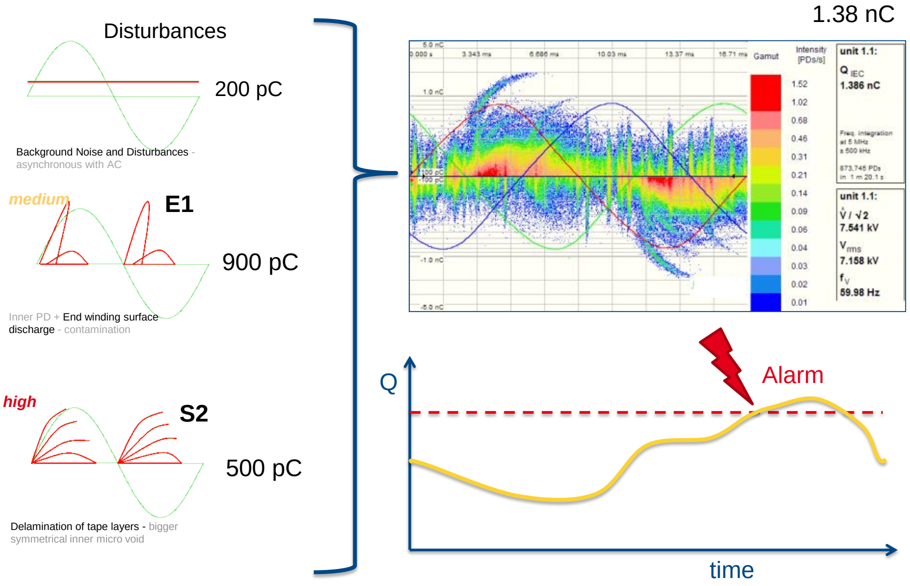


Figure 2: Superposition of various PD and noise sources during on-line monitoring of partial discharges

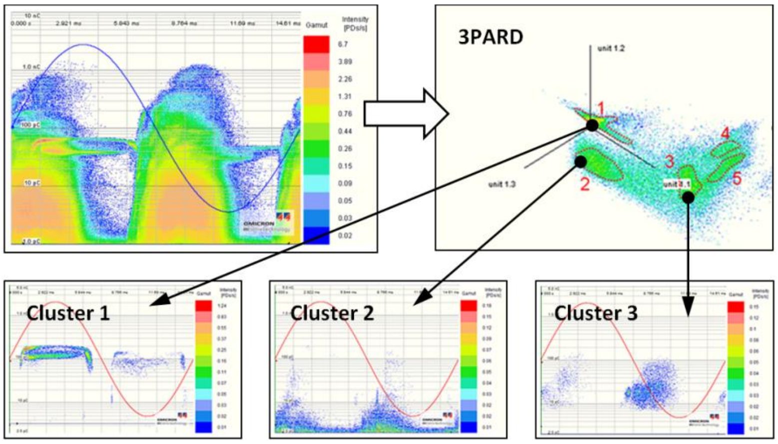


Figure 3: An example of separation of PD sources by 3PARD

3 CONDITION MONITORING OF LARGE POWER TRANSFORMERS

3.1 Transformer Tests during Outages

Today a large variety of off-line applied diagnostic tests for transformers is available. Table 3 lists the tests applied in the context of this work.

Table 3 Diagnostic tests for large generator step-up transformers during outages

Component	Diagnostic Test	Frequency
Insulation system	Oil analysis	6 or 12 months
	Dissolved gas analysis	6 or 12 months
	Furanes	2 years / After indication
	Dielectric response analysis	After indication
Windings	Winding resistance	8 years
	Transmission ratio	8 years
	Short circuit impedance	8 years
	No load current	8 years
	Frequency Response Analysis FRA	8 years / after indication
Bushings	Capacitance and dissipation factor	4 years
OLTC	Dynamic resistance	4 years

3.2 Transformer On-line Monitoring

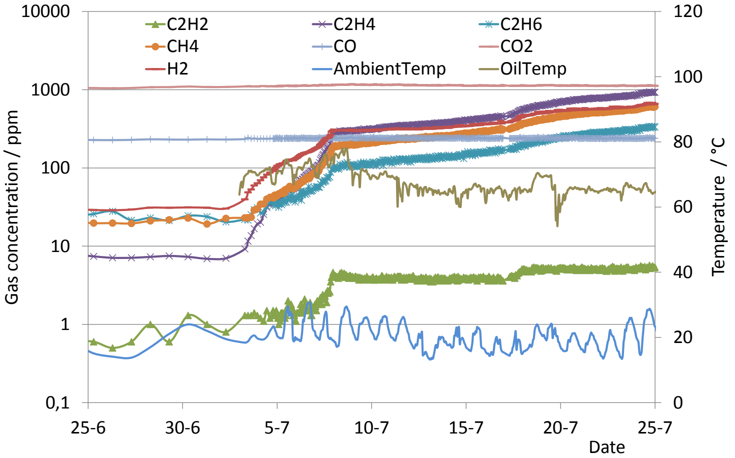
Based on international and local failure statistics, the on-line monitoring techniques of Table 4 received the highest priority.

Table 4: Diagnostic measurements for generator step-up transformers during operation (on-line monitoring)

Component	Monitored Parameter
Insulation system	Oil temperature
	Dissolved gas analysis (gas selective multi-gas systems)
	Moisture in oil
	Partial discharges
	Transient over-voltages
Bushings	Capacitance and dissipation factor
OLTC	Motor current analysis

3.3 Experiences with DGA Monitoring

The analysis of failure gases dissolved in oil (DGA) is one of the most powerful tools for diagnostics of oil-filled equipment because of the rich operation experience and the mature technical implementations. Generator step-up transformers belong to the most expensive equipment in power plants; therefore gas selective multi-gas sensors are generally preferred to sum-gas sensors. Using the single gases, advanced interpretation schemes like the Doernenburg ratios and the Duval triangles are applied.



Rule	Diagnosis
Key-Gas	PD tracking , overheating
Dörnenburg	Low and high energy discharge, ther. decomposition
Rogers	Core and tank circulating currents, overheated joints
MSS	Thermal fault
IEC60599	Thermal fault > 700°C
Duval	Thermal fault > 700°C
Cigre	Overheating
VDE	Slight overheating

Figure 4: On-line monitoring data of dissolved gases and temperature for a period of 1 month, showing strong increase of most hydrocarbons after 03. July (left) and DGA analysis rules and diagnostic results (right)

Figure 4 (left) shows the individual gases measured on-line over a time period of one month. At 03.July, the hydrocarbons strongly increased. DGA laboratory measurements from oil samples confirmed the on-line readings. Various analysis schemes were applied, pointing towards a local hot spot, although not congruently, Figure 4 (right). The very specific conclusion of the Rogers assessment rule finally agreed with the actual failure. In discussion with the transformer manufacturer the possible location of the hot spot was identified and later, after opening the transformer, confirmed. A short circuit between the tank and one field grading electrode of the winding caused circular currents which lead to over-heating and burned the oil-paper insulation.

For operation of a power plant, such early detection of an ongoing failure is of outmost importance. This allowed early planning of the outage, searching for a replacement of the transformer and performing the exchange in less than 14 days. An unplanned outage e.g. based on Buchholz tripping might easily result in an outage of months duration with large consequent financial losses.

3.4 Experiences with Bushing Monitoring

Since bushings are subjected to high dielectric and thermal stresses; bushing failures are one of the root causes of forced outages and transformer failures. These are even connected with bushing explosions. For monitoring the dielectric integrity of bushings, three measurement parameters cover all important bushing failure modes: bushing capacitance, dissipation factor (tangent delta) and partial discharges. In the context of this work a combined measurement of these parameters is performed by one instrument connected to the bushing taps.

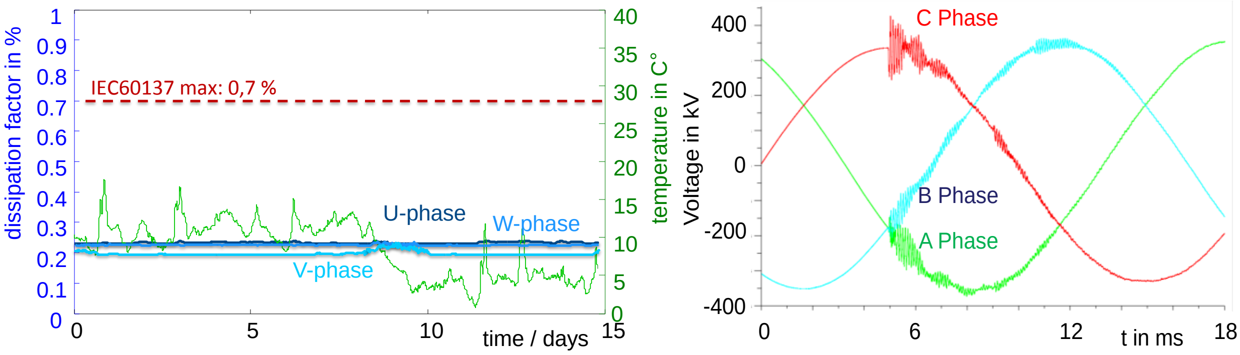


Figure 5: On-line measurement of bushing dissipation factor (left) and transient over-voltages measured at 400 kV bushings (right)

The needed accuracy for reliable detection of failures is in the range of 5 pF for capacitance and 0.1 % for dissipation factor. For this measurement, generally a reference signal is necessary but in the on-line application, the phase voltage is not directly available. Therefore various approaches for obtaining such reference signal were investigated with the result, that the secondary voltage of voltage transformers provides the highest accuracy [6]. In various field installations a typical overall system accuracy (including voltage transformers) of ± 2 pF for capacitance and ± 0.05 % for dissipation factor was reached, even without further data processing like averaging. In case voltage transformers are not available, bushings of a second transformer provide the reference signal. This principle was used for the results shown in Figure 5 (left). The dissipation factor of three bushings vs. time shows a week dependence on temperature, but even without automatic temperature compensation, the measurement is stable and accurate. Temperature was measured in the bushing flange. Between days 8 and 10, heavy rain lead to a drop in temperature and made the bushing surfaces wet, resulting in the visible slight increase of dissipation factor.

The accuracy of this system can be compared to accurate off-line measurements, consequently standards from off-line tests like IEC 60137 are implemented as warning and alarm levels. With this solution, online monitoring is not only trending, but provides the accuracy for clear good / bad evaluation and maintenance decisions.

3.5 Experiences with Transient Over-Voltage Recording

Transient over-voltages originate from events in the HV grid and may lead to pre-mature insulation ageing. After the experiences of the power plant operators, over-voltages are likely the reason for a historical catastrophic transformer failure. However, there are extremely limited possibilities to regularly monitor transient over-voltages and to make a full recording of the time signal up so several MHz. In the context of this paper, transient over-voltages are recorded via the bushing tap. Measurements of the transmission behaviour of bushings proved their linearly capacitive behaviour until at least 16 MHz. Figure 5 (right) shows transient over-voltages measured at two parallel power transformers at the

400 kV side, where oscillations of 10 kHz and superimposed oscillations of 600 Hz frequency are visible. The reason for these oscillations is under investigation.

3.6 Experiences with Partial Discharge Monitoring

Partial discharge (PD) is a localized dielectric breakdown of a small portion of a solid electrical insulation system. Since partial discharges are early indicators of incipient faults, their on-line observation is of prominent interest. Acceptance criteria in the factory test of power transformers are an apparent charge of less than 5 pC for bushings (IEC 60137) and less than 300 pC for power transformers (IEC 60076-3).

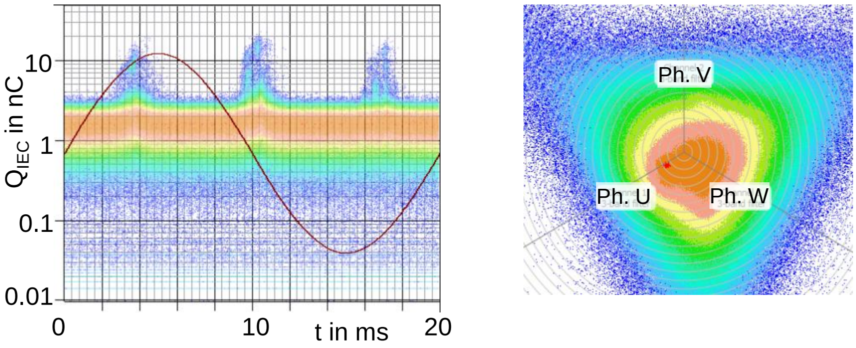


Figure 6: PRDPD pattern of electrical on-line measurement at bushing taps (left) and corresponding 3PARD (right).

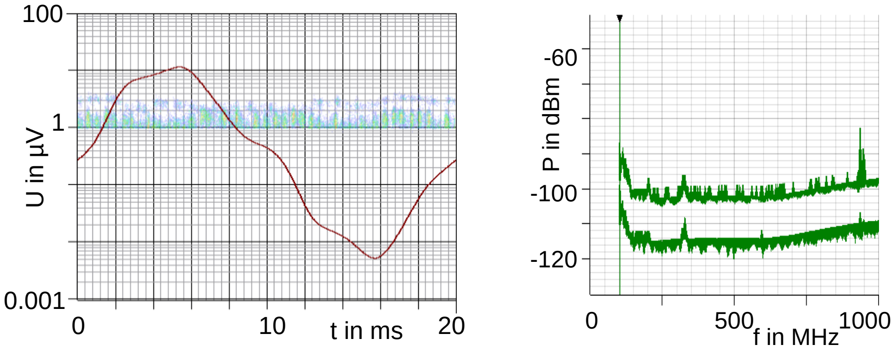


Figure 7. UHF PRPD measured with drain valve sensor (left) and frequency sweep of drain valve sensor (right).

For on-line measurement of partial discharges, two measurement principles are popular: (1) detection of electrical signals at the bushing taps and (2) detection of electromagnetic waves with UHF sensors. On-line partial discharge measurements are subject to an immanent thread: the discrimination between external corona and internal, "true" partial discharges. Solely measurements at the bushing taps struggle with this discrimination. Figure 6 (left) depicts phase resolved partial discharge patterns (PRPD) for three phases, measured at the bushing taps. The apparent charge after IEC ranges from 8 to 20 nC, depending on weather conditions. Recalling the acceptance criteria, this transformer seems to develop a failure. Actually, this high PD activity is originated by corona within the substation. After our experiences, solely electrical PD measurements at the bushing taps are useless for observing the transformers insulation health.

While electro-magnetic disturbances pollute the environment outside the transformer tank, the transformer tank is free of discharges. Drain valve or hatch type UHF sensors inside of the transformer tank pick up internal electromagnetic impulses from partial discharges and are at the same time immune against external corona. The combination of signals in the UHF range with electrical signals from the bushing tap promises to provide a high sensitivity together with suppression of external noise like corona. Figure 7 proves this with the UHF PRPD (left) and the UHF frequency sweep (right). The UHF PRPD shows only instrument noise of very low amplitude, i.e. 3 µV. In the frequency sweep, measured while tuning the UHF receiver from 180 to 2000 MHz, only very week signals from mobile radio transmitters are visible e.g. at 890 MHz. These conditions allow for a sensitive and noise-robust detection of inner partial discharges. In this context, the combination with electrical measurements at the bushing taps provides additionally phase information and often a higher sensitivity to internal defects than sole UHF measurements. Additionally, software-based correlation algorithms like the 3PARD in Figure 3 can help to separate various PD or corona sources.

3.7 System Design for Combined Monitoring of Generator and Transformer

This section describes one example of a field installation. At a large brown coal power plant, one 900 MW block was equipped with a monitoring system for the parameters:

- Partial discharges at the 900 MW generator measured with capacitive couplers
- Partial discharges at two 1.1 GVA transformers, including electrical and UHF PD detection
- Transient over-voltages at both transformers
- Capacitance and dissipation factor of both transformers

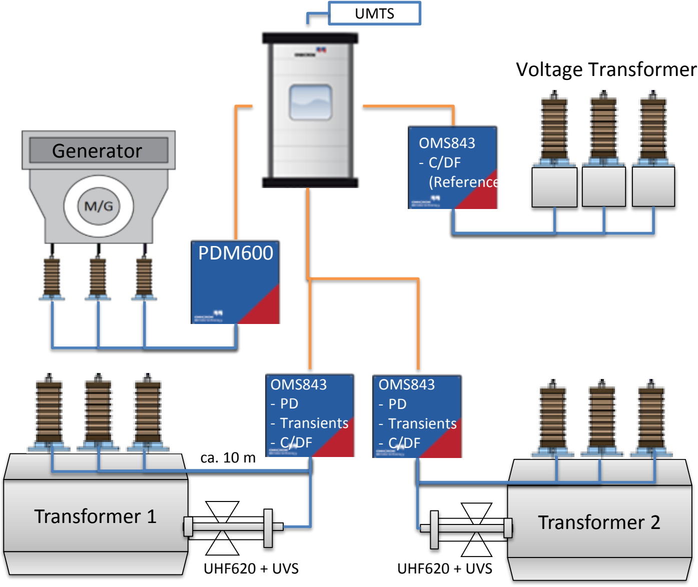


Figure 8: System design for combined monitoring of generator and two transformers at a 900 MW power unit of a lignite fired power plant

Figure 8 illustrates the design of the monitoring system. In this case, three reference principles for calculating capacitance and dissipation factor were compared; the sum of currents, phase-to-phase comparison and VT reference. The power plant operator had particular interest to monitor transient over-voltages in the grid, as historically transformer breakdowns were attributed to lightning strokes. For PD monitoring, both the electrical measurement at the bushing taps and the UHF method were combined. All monitoring acquisition units are directly mounted at the HV equipment and are synchronized via fibre-optic cables. A central computer stores and evaluates the data, generates warnings and alarms and provides a web interface. Via common web browsers, users can log into the system, access the data, change alarms etc..

4 BIBLIOGRAPHY

[1] P. Jarman et al.: "Recommendations for condition monitoring and condition assessment facilities for transformers", Cigré WG A2.27, Technical Brochure 343, on-line available at www.e-cigre.org

[2] Brütsch et al. "Insulation Failure Mechanisms of Power Generators", DEIS July/August 2008

[3] J. Linton et al.: "Generator Maintenance, Inspection and Test Programmes", Cigré WG A1.07, Technical Brochure 386, on-line available at www.e-cigre.org

[4] A. Obralic, W. Koltunowicz and A. Belkov: "Automatisches Mustererkennungsverfahren bei TE-Monitoring an rotierenden elektrischen Maschinen", ETG Diagnostik elektrischer Betriebsmittel, Fulda 2012

[5] W. Koltunowicz and R. Plath, "Synchronous multi-channel PD measurements", IEEE Transactions on Dielectrics and Electrical Insulation, vol.15, no.6, December 2008, pp. 1715-1723.

[6] M. Koch, M. Krüger, M. Lukas " Ein neues Verfahren zum Online-Monitoring von Durchführungen, Transienten und Teilentladungen an Transformatoren", ETG Diagnostik elektrischer Betriebsmittel, Fulda 2012