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A new method for on-line monitoring of bushings, transients and PD of power transformers

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Abstract

This paper describes a new on-line method for capacitance and dissipation factor measurements of high voltage bushings, for recording grid transients and for partial discharge monitoring at power transformers. The needed accuracy for reliable detection of failures is in the range of 5 pF for capacitance and 0.1 % for dissipation factor. To overcome these shortcomings, this paper introduces an absolute method for measuring capacitance and dissipation factor of HV bushings. As for off-line measurements, the discrimination between noise and true internal discharges is the key for successful diagnosis. Strategies for sensitive partial discharge measurements under disturbed on-line conditions are described, also involving measurements in the UHF range.

Keywords: power transformers, bushings, on-line monitoring, dissipation factor, capacitance, PD, UHF.

Nowe metody monitoringu on-line przepustów, przepięć i wyładowań niezupełnych transformatorów energetycznych

Streszczenie

Artykuł opisuje nowe metody pomiaru on-line pojemności i współczynnika strat przepustów wysokonapięciowych na potrzeby, monitorowania przepięć w sieci i wyładowań niezupełnych w transformatorach energetycznych. Według statystyk awaryjności przepusty WN są jedną z głównych przyczyn awarii transformatorów, co motywuje operatorów do ciągłego monitoringu on-line stanu układów izolacyjnych. Na potrzeby wiarygodnej diagnostyki wymagana jest dokładność pomiaru pojemności rzędu 5 pF i współczynnika strat rzędu 0,1%. Aby uzyskać taką rozdzielczość, wskutek braku symetrii w sieci, nie wystarczy względne porównanie prądów mierzonych w zaciskach pomiarowych w przepustach trzech faz. Dodatkowo, ten sposób pomiaru nie pozwala identyfikować procesu starzenia przebiegającego w trzech fazach ze zbliżonym tempem. W artykule przedstawiono metodę pomiaru rzeczywistych wartości pojemności i współczynnika strat przepustów WN. Pozwala ona uzyskać dokładność podobną do pomiarów off-line nawet w warunkach eksploatacyjnych. Wyładowania niezupełne są wczesnym wskaźnikiem zbliżającego się przebicia w izolacji WN. Ich pomiar na zacisku przepustu WN umożliwia wykrycie defektów w izolacji przepustu oraz transformatora. Podobnie jak w pomiarach off-line, rozróżnienie zakłóceń od rzeczywistych wyładowań wewnętrz izolacji jest kluczem do poprawnej diagnostyki. Opisano strategie czułego pomiaru wyładowań niezupełnych w warunkach on-line, z uwzględnieniem zakresu UHF.

Słowa kluczowe: transformator energetyczny, przepust, monitoring on-line, współczynnik strat, pojemność, WNZ, UHF.

1. On-line monitoring of power transformers

For many decades, transformer users have sought ways to assess the general condition and identify specific problems of their assets. Conclusively, diagnostic tests applied in the de-energized status have been developed. 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 condition;
- Early diagnosis of initiating failures for scheduling maintenance actions, therewith supporting condition based maintenance schemes;
- Knowledge of the equipment historical use for fully utilizing the life span in the context of asset life management.

Beside these advantages, on-line monitoring of power transformers is apparently becoming an essential feature of the "smart" electric utility systems of the future.

Still, not all of these promises are fulfilled with today's monitoring solutions, as experts discuss questions like "How to get real value from continuous on-line monitoring systems?" [1].

This paper describes a new method for the monitoring of capacitance and dissipation factor (power factor) of transformer bushings, transients in the HV grid and partial discharges in the transformer and its bushings. Particular focus is given on an extraordinary high accuracy of all measurement values; an accuracy, which allows moving forward from a "warning" system to "advanced diagnostics"; in some functions even to replace off-line tests.

Since bushings are subjected to high dielectric and thermal stresses; bushing failures are one of the root causes of forced outages and transformer failures. Fig. 1 shows transformer failure statistics, compiled by the authors of [2] from 7 other sources. Bushings contribute essentially with about 20 %. Failures in the winding are often emitting partial discharges and can be a result of transient over-voltages in the electrical grid. Thus, a monitoring system for the bushings capacitance and dissipation factor, partial discharges and grid transients will likely lower the failure probability of the complete asset.

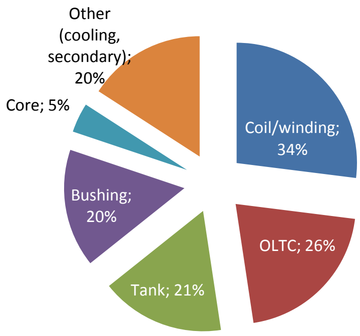


Fig. 1. Reasons for transformer failures
Rys. 1. Przyczyny awarii transformatorów

2. Monitoring of bushing capacitance and dissipation factor

Bushing failure modes and requested sensitivity

A monitoring system for HV bushings should early detect common failure mechanisms for transformer bushings.

Partial breakdowns between field grading layers result in an increase of capacitance and in partial discharges. Table 1 gives the increase of capacitance for bushings of different voltage levels with their typical number of field grading layers.

Tab. 1. Voltage class and change of capacitance for condenser type bushings
Tab. 1. Klasy napięciowe i zmiany pojemności przepustów kondensatorowych

Voltage in kV	No. of layers	Change in %
123	14	7.1
245	30	3.3
420	40	2.5
550	55	1.8

Ageing and moisture increase the dissipation factor DF or power factor PF. Standards as in Table 2 give advice on evaluating the test results for resign-impregnated-paper RIP, oil-impregnated-paper OIP and resign-bounded-paper bushings. Consequently, monitoring systems should be able to provide an appropriate accuracy to evaluate the bushings condition according to the relevant standards.

Tab. 2. Acceptance level of dielectric losses for bushings of different design
Tab. 2. Dopuszczalne straty dielektryczne w przepustach różnych konstrukcji

Standards	RIP	OIP	RBP
DF IEC60137	<0.7%	<0.7%	<1.5%
PF IEEE C57.19.01	<0.85%	< 0.5 %	< 2 %

Further failure mechanisms are *voids and cracks*, resulting in partial discharges and a slight change of capacitance and finally corroded contacts, resulting in partial discharges.

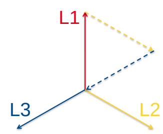
From the considerations above we can draw the conclusion that a monitoring system with sensitive measurement of capacitance, dissipation factor and partial discharges has the capability of an early diagnosis of all typical initiating failure modes.

The reference problem

For measuring capacitance or dissipation factor, generally a reference signal is necessary. For off-line measurements, the applied test voltage is measured and used as reference. In the on-line application, the applied voltage – now the phase voltage – is not directly available. Therefore various approaches for obtaining such reference signal were investigated.

The oldest approach for calculating a parameter similar to capacitance and dissipation factor on-line is the *relative measurement* or the *sum of currents*, based on a comparison between the three phases of the three-wire system. The three phase voltages or their equivalent currents are measured at the bushing taps using a capacitive divider, consisting of the bushing capacitance C_1 and a secondary capacitance. Under symmetric grid conditions, a vectorial addition of all three phasors should end up in the origin of the diagram, Fig. 2 (a). Still, practical measurements under real conditions show that the three phasors do not exactly end up in the origin. Even more severe is that load imbalances and mutual coupling make the result of the vectorial addition very unstable. The authors of [3] reported similar experiences. Fig. 2 (b), depicts practical measurement results for a time period of only two days, already leading to a systematic error of + 0.3 to – 0.4 %. Conclusively, while looking at the accuracy specification given by the standards, Table 2, the relative dissipation factor measurement cannot be used for assessing the dissipation factor according to the relevant standards.

a)



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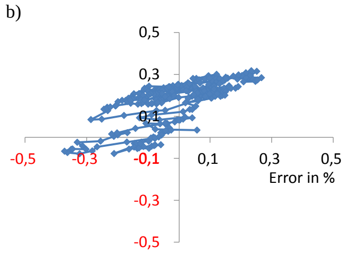


Fig. 2. Principle of the relative dissipation factor measurement (a) and systematic errors under practical conditions (b)
Rys. 2. Zasada pomiaru względnego współczynnika strat (a) i systematyczne błędy w pomiarach eksploatacyjnych (b)

Phase-to-phase comparison

Another variation of a relative measurement is to compare the individual bushing to the bushing of the same phase of another transformer of the same voltage level. While this approach would eliminate the influence of imbalances of the three phase voltages, it is subject to other disadvantages:

- Second bushing of the same voltage level needs to be available,
- Simultaneous ageing and therefore increase of the dissipation factor cannot be detected.

Use of the stray capacitance

Electrical fields, oscillating with the power frequency, are readily accessible in any HV substation. These fields may be coupled into some electrode arrangement by the stray capacitance. Researchers attempted to derive a reference signal for measuring the capacitance and dissipation factor from these fields [4]. The authors of this paper attempted to apply this reference method in life substations and dealt with the following difficulties:

- Strong influence of electrical fields emitted from neighboring HV systems,
- Disturbances due to currents over the bushing surface,

Therefore the accuracy requirements neither for capacitance nor for dissipation factor could be fulfilled.

Voltage transformers as reference

Voltage transformers (VTs), also referred to as "potential transformers" (PTs), are used for measuring voltage in electrical power systems, and for power system protection and control. VTs are designed to have an accurately known transformation ratio in both magnitude and phase and are available in virtually any HV substation. Fig. 3 depicts the system design for a measurement of capacitance and dissipation factor with the VTs of the individual phase as references. The acquisition units at the bushings and at the VT's are connected to a data storage system by fiber optics, ensuring galvanic decoupling and avoiding phase delays.

Fig. 4 depicts the on-line measurement results for capacitance and dissipation factor including the warning levels according to Table 1 and 2. The on-line measured *capacitance value* was 467 pF with a variation of less than ± 2 pF for a time period of 1.5 years. The off-line measured reference value was 467.1 pF. For *dissipation factor*, the off-line value was 0.27 %. The on-line measurement determined the dissipation factor with the same result of 0.27 % and had a variation of only 0.05 % over a time period of 1.5 years.

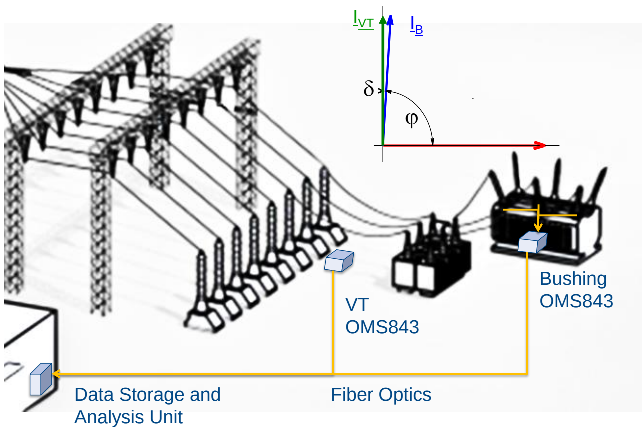


Fig. 3. System design for measuring bushing capacitance and dissipation factor with voltage transformers as reference

Rys. 3. Układ do pomiaru pojemności i współczynnika strat przepustu ze wzorcowym przekładnikiem napięciowym

Conclusively, in our investigations, only the use of the VT reference for on-line measurements of capacitance and dissipation factor allows for the application of assessment limits according to relevant standards. Moreover, it provides an accuracy similar to off-line tests.

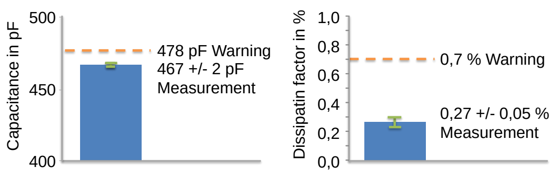


Fig. 4. Measurement results for on-line measurement of capacitance and dissipation factor including variations over a time period of 1.5 years, with warning levels

Rys. 4. Wyniki pomiaru on-line pojemności i współczynnika strat w okresie 1,5 roku z uwzględnieniem wahań

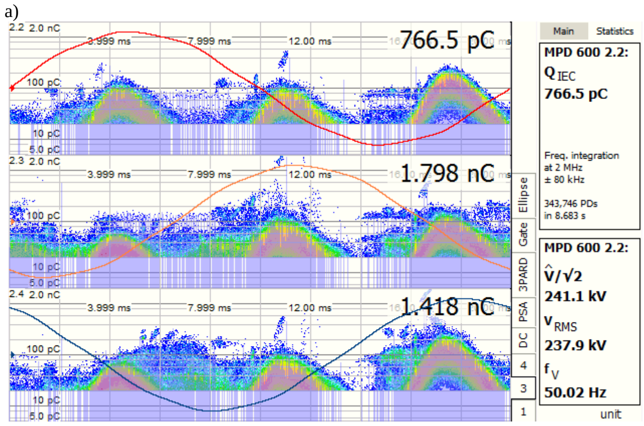
3. On-line partial discharge measurement

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 is an apparent charge of less than 5 pC for bushings (IEC 60137) and less than 300 pC for power transformers (IEC 60076-3).

Electrical PD measurement at the bushingt

For on-line measurements 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 subjected to an immanent thread: the discrimination between external corona and internal, "true" partial discharges. Solely measurements at the bushing taps struggle with this discrimination. Fig. 5 (a) depicts phase resolved partial discharge patterns (PRPD) for three phases, measured at the bushing taps. Fig. 5 (b) shows the apparent charge vs. time for a period of 4 days, ranging from 100 pC to 8 nC. Recalling the acceptance criteria, this transformer seems to develop a failure. Actually, this high PD activity, is originated by corona within the substation. Conclusively, solely electrical PD measurements at the bushing taps are simply useless for observing the assets health.

a)



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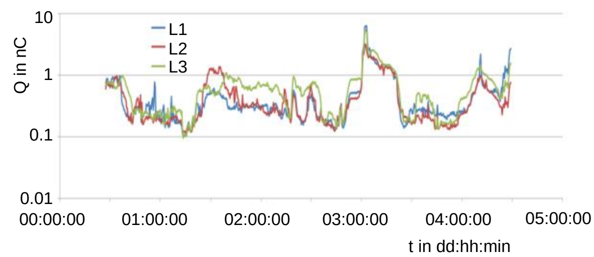


Fig. 5. PRPDs of on-line measured partial discharges coupled out at the bushing taps (a) and partial discharge activity over a time period of four days (b)

Rys. 5. PRPD dla pomiarów on-line WNZ na zaciskach przepustów (a) oraz zmiany ich ładunku w okresie czterech dni (b)

Electromagnetical measurements with UHF sensors

The transformer tank functions as a shield against external partial discharges, thus internal partial discharges can be detected relatively undisturbed by their electromagnetic waves [5]. These are acquired by drain valve or hatch type sensors. 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. The UHF signal serves as a trigger or gating signal for the electrical signals. Fig. 6 (a) illustrates this combination. Fig. 6 (b) shows the individual PD patterns of electrical signals at the bushing tap and UHF signals from a drain valve sensor. The individual PD patterns do not allow for a pattern classification. After their combination, where the UHF signals serve as gating signals, a PD pattern can be recognized. The validity of the apparent charge after IEC (Q_{IEC}) is here limited due to the different propagation mechanisms of electrical and UHF signals. The transformer was later dismantled, the PD test repeated in the factory and a similar pattern received [6].

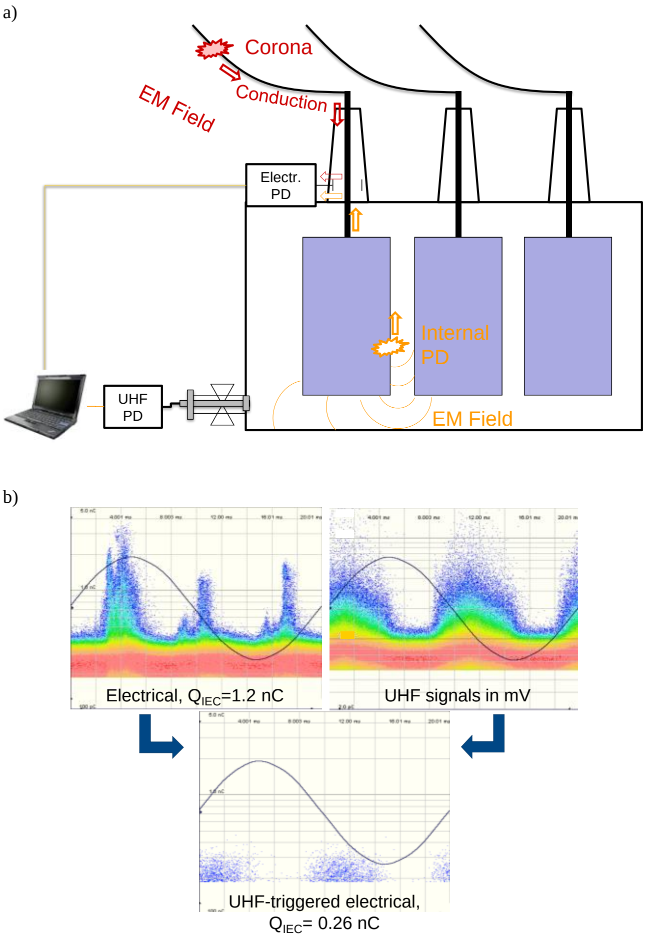


Fig. 6. Schematic diagram of combined electrical and UHF PD measurements (a) and combination of electrical and UHF PD signals with resulting PD pattern (b)

Rys. 6. Schemat jednoczesnego pomiaru WNZ metodą elektryczną i UHF (a) oraz wyniki pomiarów tymi metodami wraz z wynikowym obrazem WNZ (b)

Noise surpression with correlation methods

Modern, digital PD measurement systems allow for a number of advanced correlation methods for noise suppression and discrimination between different PD sources. These methods are of high relevance for the on-line application.

One of these correlation methods is the three phase amplitude relation diagram, 3PARD, [7]. Three synchronously operating PD instruments make it possible to detect the same PD impulse at different places, i.e. at the three phases. Now the amplitudes, measured by the individual PD instrument, are depicted in a star-type diagram. Each PD source has a specific propagation path to the measurement points (bushing taps), resulting in a different amplitude. Depicted in the diagram, each PD source forms an individual cluster, Fig. 8.

Another type of correlation diagram is the three center frequency correlation diagram, 3FREQ. With this diagram, the spectrum in frequency domain of individual PD pulses is evaluated for discriminating pulses coming from different sources.

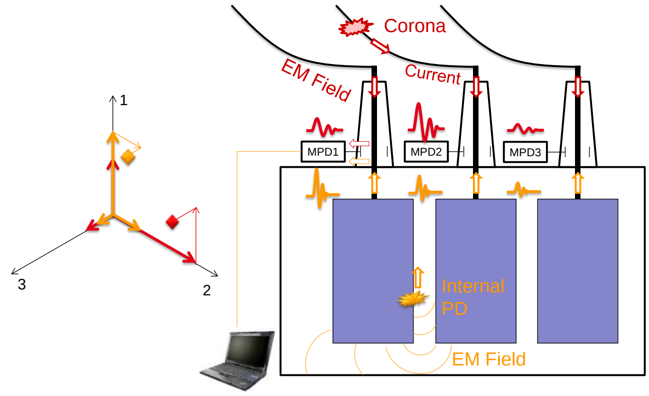


Fig. 8. Principle of 3PARD for discriminating between different PD sources based on their amplitudes

Rys. 8. Zasada działania metody 3PARD rozróżniania źródeł WNZ w oparciu o ich amplitudy

One digital PD measurement system is operating with three center frequencies, in Fig. 9 below these are exemplarily 0.5, 2 and 8 MHz. The amplitudes in frequency domain for these three frequencies are depicted at a star-type diagram, allowing for a discrimination of sources based on their frequency spectra.

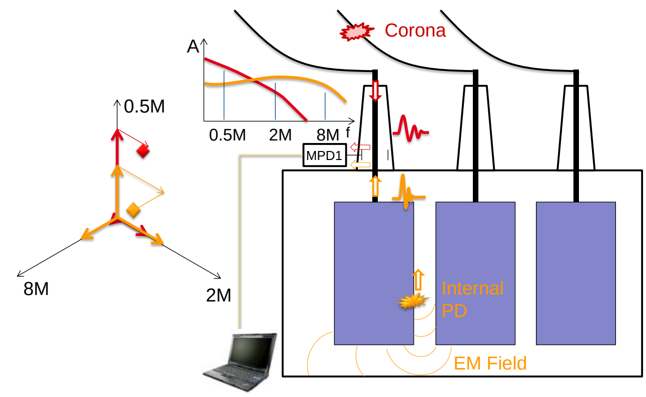


Fig. 9. Principle of 3FREQ for discriminating between different PD sources based on their frequency spectra

Rys. 9. Zasada działania metody 3FREQ rozróżniania źródeł WNZ w oparciu o ich spektra częstotliwościowe

4. Case study: on-line monitoring of a large power plant

At a large brown coal power plant, one 900 MW unit was equipped with a monitoring system for the parameters:

- Partial discharges at the 900 MW generator
- 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

Fig. 10 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. Corona discharges dominate the electrical signals, with an apparent charge of about 18 nC.

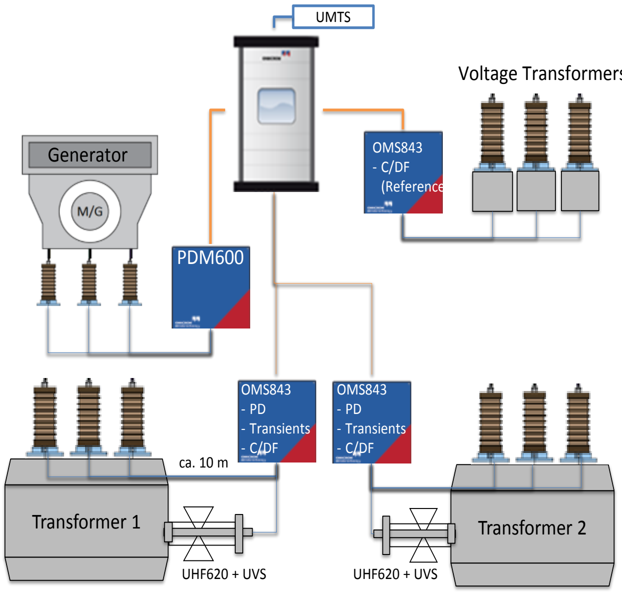
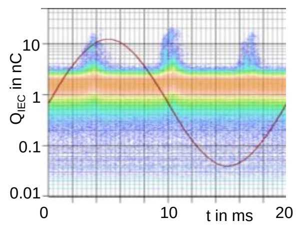


Fig. 10. System design for combined monitoring of generator and two transformers at a 900 MW power unit of a thermal power plant

Rys. 10. System jednoczesnego monitoringu generatora i dwóch transformatorów w elektrowni konwencjonalnej o mocy 900 MW

Signal coupling between the conductors of the three-phase system lead to the three peaks, shifted by 120 ° in Fig. 11 (a). Also the 3PARD representation is dominated by corona phenomena, Fig. 11 (b).

a)



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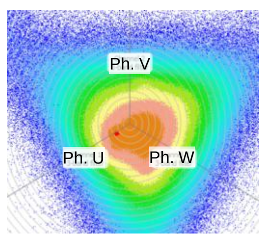
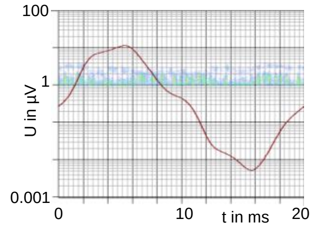


Fig. 11. PRDPD pattern of electrical on-line measurement at bushing taps (a) and corresponding 3PARD (b)

Rys. 11. Obraz PRDPD elektrycznego pomiaru on-line na zaciskach przepustów (a) i odpowiadający mu 3PARD (b)

While electro-magnetic disturbances pollute the environment outside the transformer tank, the transformer tank is free of discharges. Fig. 12 proves this with the UHF PRPD (a) and the UHF frequency sweep (b). 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.

a)



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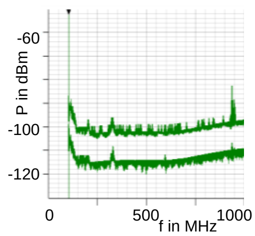

Fig. 12. UHF PRPD measured with drain valve sensor (a) and frequency sweep of drain valve sensor (b)

Rys. 12. UHF PRPD zmierzone czujnikiem w zaworze (a) i częstotliwościowy rozkład sygnału czujnika (b)

5. Conclusions

This paper describes a new on-line monitoring system for measuring bushing capacitance and dissipation factor, grid transients and partial discharges of transformer and bushing. While using voltage transformers as reference, it provides an accuracy comparable to off-line bridge instruments. For partial discharge measurements, various methods for discriminating between internal discharges and external noise are described: UHF gating and correlation diagrams based on amplitude ratios and frequency content. The on-line monitoring system aims to provide reliable, automated on-line monitoring functions for observation and warning and, with the same hardware, an advanced diagnostic tool in case of insulation failures.

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