Experiences with Digital Analysis of Discharges in High Voltage Components

Key Words: Partial discharge, measurements, diagnostics, pattern recognition, high voltage equipment, insulation condition

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Digital PD processing provides several quantities to evaluate discharges in HV equipment.

The main goal of PD diagnosis is to recognize high voltage insulation problems and to identify the insulation defect causing the discharge: e.g., internal or surface discharges, corona, treeing, etc. This information is vital for estimating the harmfulness of the discharge.

Manufacturers of HV equipment, together with producers and distributors of electrical power, have a growing interest in on-site, off-line and on-line analysis of PD in existing HV components. The objective of such analysis is the early recognition and location of possible insulation failures in HV equipment. As a result, maintenance actions can be planned to prevent unexpected interruptions in equipment utilization. Furthermore, based on knowledge of the type of discharge and its behavior over time, important information can be obtained regarding degradation processes.

The ability of digital PD analyzers to process and store specific information concerning discharge activity can be used for various purposes: discharge recognition, condition monitoring, etc. [1-15]. To exploit these possibilities, a specific fingerprint technique has been successfully used in recent years for off-line and on-line PD measurements of HV components [12, 16-18].

In this paper diverse practical examples are discussed of applying advanced digital post-processing for the measurement of partial discharges.

PD Database for Decision Support

The development of a PD database to support the discharge evaluation during periodic off-line inspections of HV components is of great importance. In this paper, based on PD measurements of various HV components, the importance of digital analysis of PD signals and the development of PD databases to

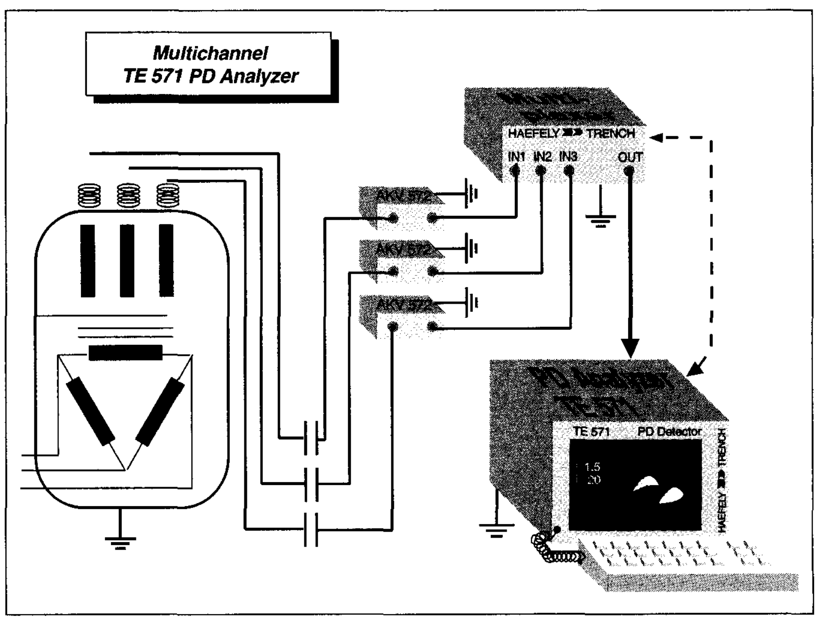

Fig. 1 Schematic diagram of a transformer test circuit using a multichannel digital PD analyzer

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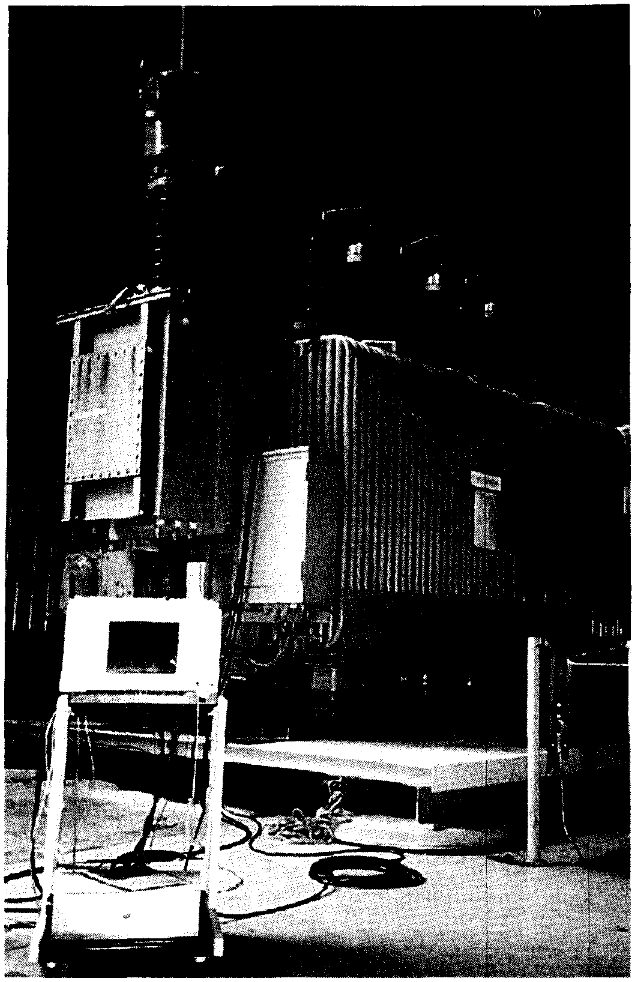


Fig. 2 PD diagnostic test on a 50/10 kV, 14/10 MVA power transformer using a digital PD analyzer (HV Laboratory, TU Delft, The Netherlands)

support the discharge evaluation during periodic off-line and on-line inspections of HV components will be discussed.

It is known that important conclusions are made regarding the condition of the test object insulation based on periodic off-line PD measurements. It is also known that several types of HV apparatus are not discharge free. On the contrary, a certain level of discharges is often allowed. Furthermore, the interpretation of measurement results often depends on the subjective opinions of test engineers.

With the advance of digital processing, the task of data acquisition and evaluation can now be performed more efficiently. In the last five years several commercial products have been introduced and are in use around the world. Moreover, to support the sharing of experience with regard to recognition, classification, and discrimination of different discharge types, a data standard has been introduced by CIGRE [19].

In the past, a strong relationship has been found between the shape of the (phase resolved) PD patterns that occur in relationship to the power frequency sine wave and the type of defect causing them. From a practical point of view it was

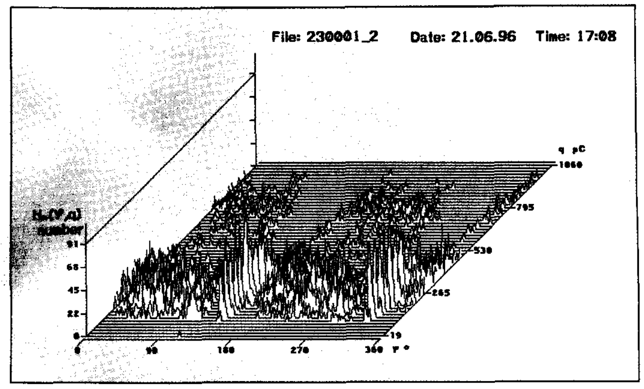


Fig. 3 Regular 3-D discharge pattern $H_n(\varphi,q)$ for a 203 MVA transformer in good condition

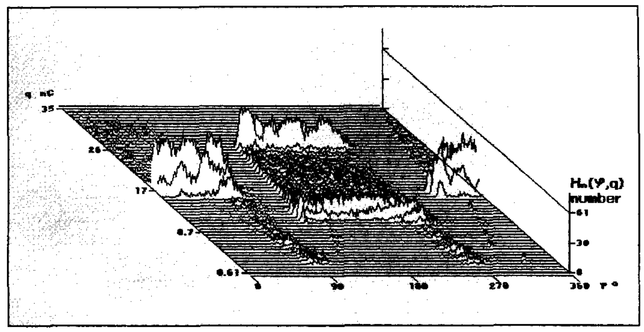


Fig. 4 Irregular 3-D discharge pattern $H_n(\varphi,q)$ observed for a 55 MVA reactor exhibiting PD on a damaged screen inside the test object

shown that two types of PD patterns are of particular interest for interpreting PD measurements:

Regular PD patterns: which are characteristic of a particular type of HV component with insulation in good condition (see Figs. 3 and 8);

Irregular PD patterns: representing certain unacceptable discharge sources. These may be related to manufacturing defects or to the effects of ageing during service life (see Figs. 4 and 9).

This study describes PD databases created for two main areas of application: induced voltage tests of power transformers and reactors (based on measurements of 80 different units), and off-line PD measurements of turbogenerators (based on measurements made over the last two years on 20 different units with ratings of 6 MW and 63 MW). In both cases the PD analysis system described in [16-18] was used.

PD Database for Power Transformers and Reactors

When a measurement has been made on a test object (see Figs. 1-2) it can be compared with a PD database comprising a collection of previous PD tests. For reasons of clarity, the PD database has been divided into two separate parts. The first part consists of measurements made on reactors, whereas the second part concerns only auto-transformers and three-phase transformers. The main goal of this PD database was to answer questions about general trends in regular or irregular PD

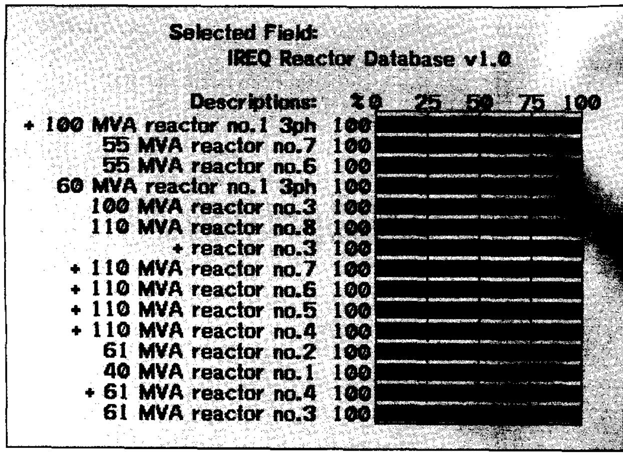


Fig. 5 Computer-aided recognition of regular PD patterns using a PD database for reactors. Typical is the overlap with other reactors also showing regular PD patterns. (+), (–), ( ) represents a test object in the database characterized by a (regular), (irregular), (unknown) pattern, respectively.

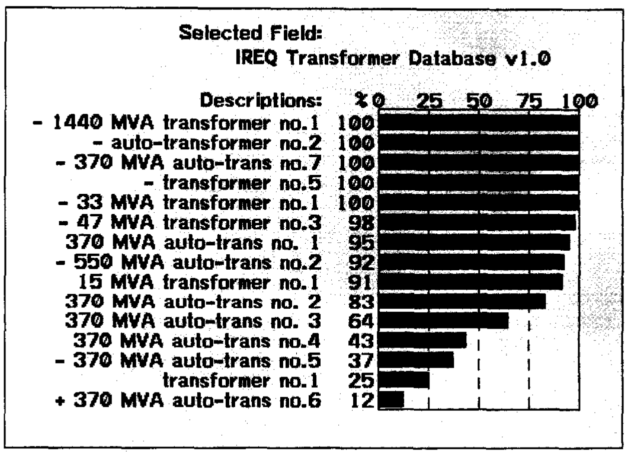


Fig. 6 Computer-aided recognition of irregular PD patterns using a PD database for transformers. Typical is the overlap with other transformers also showing irregular PD patterns. (+), (–), ( ) represent a test object in the database characterized by a (regular), (irregular), (unknown) pattern, respectively.

patterns occurring during induced voltage testing of power transformers and reactors. In the following, two examples are given showing an application of both PD databases during the classification of an unknown measurement. As observed in [10], the classification of an acceptable PD pattern using a database (Fig. 5) often resulted in multiple correlation. In most of these cases a low discharge magnitude and low discharge intensity was observed (+). No correlation was found to unacceptable PD patterns. When a typical defect was classified, correlation was found to only a few patterns (Fig. 6), most of which had shown unacceptable PD.

PD Database for Turbogenerators

When discharge data are measured during periodic inspections every few years, PD patterns of separate coils can be compared with those observed during previous inspections. Based on this experience, several characteristics have been found to describe typical insulation problems of stator insulation [21]. Several groups of PD patterns have been

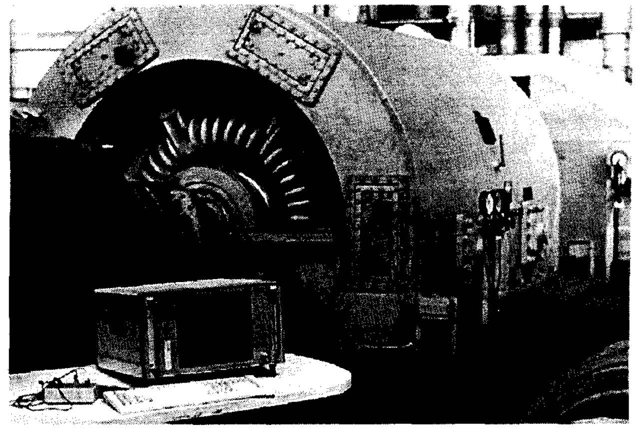


Fig. 7 Off-line periodic PD inspection of a 63 MW turbogenerator using a digital PD analyzer (ABB Dolmel Ltd., Poland)

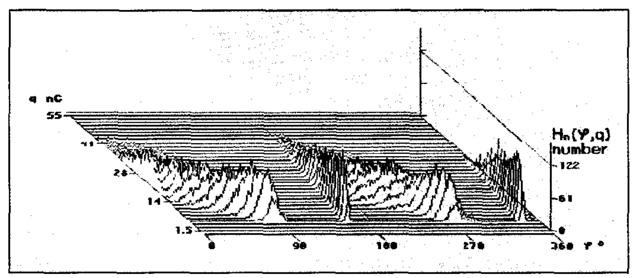


Fig. 8 Example of a regular PD pattern observed in a 63 MW turbogenerator: The outer and inner sinusoidal shapes of the 3D phase-resolved distribution $H_n(\gamma,q)$ are typical for turbogenerators in good condition.

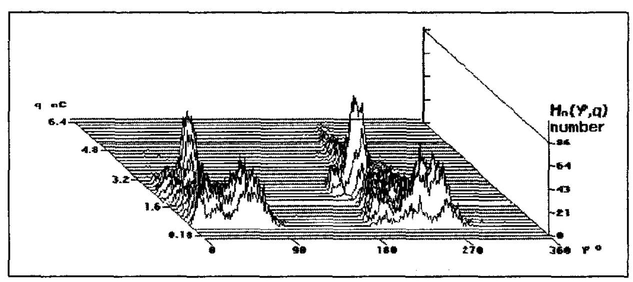


Fig. 9 Example of an irregular PD pattern observed in a 6 MW turbogenerator. This $H_n(\gamma,q)$ phase-resolved distribution was observed in the presence of end winding discharges

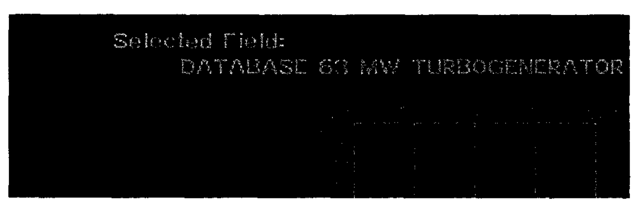


Fig. 10 Example of pattern recognition using the 63 MW turbogenerator database in the case of an irregular PD pattern; the high % represents classification as slot discharges.

identified in the case of irregular PD patterns. Based on various inspections and repairs the following discharge sources were found during periodic PD measurements:

a) PD in the HV bushings,

b) PD in a slot section caused by damaged outer corona protection,

c) PD in the end winding section.

Such PD patterns were also observed by Stone [22-23]. As a result, two PD databases have been developed to support the recognition of insulation degradation during periodic off-line inspection, one for 6 MW and one for 63 MW units. Figs. 10 and 11 show the classification of a particular defect using these databases. Both examples confirm that the PD patterns measured for particular defects can be used for identification of these defects.

The digital classification of PD patterns observed during periodic PD measurements on HV components has made it possible to develop a decision support database for discharge faults. Two different ways of constructing a PD database have been shown. One provides a distinction between objects in good condition and objects showing unacceptable discharges. The other confirms the possibility of identifying the source of the discharge in the insulation.

It has also been demonstrated in [24] that it is sometimes possible to distinguish between components in good condition and those that show internal or external discharges originating from insulation degradation using this technique.

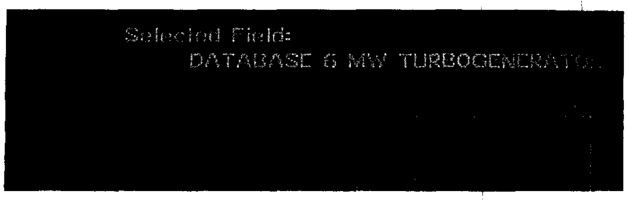


Fig. 11 Example of pattern recognition using the 6 MW turbogenerator database in the case of an irregular PD pattern; the high % represents classification as end winding discharges.

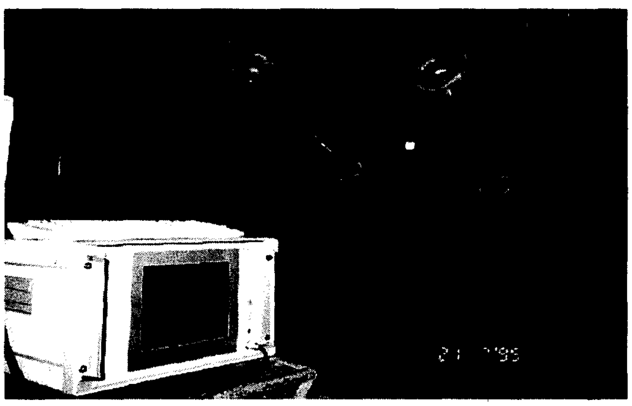


Fig. 12 Digital PD detector for location of defects in HV cables (NKF Kabel B.V. Delft, The Netherlands)

Fig. 13 Indication of discharge site location at 1194 m in a 1785 m long, plastic-insulated HV cable

Digital PD Location in HV Cables Using the Traveling Wave Method

Partial discharges occur in gas-filled cavities in a dielectric and cause a gradual erosion of the insulation material. For this reason the location of PD in HV cables is important for quality control. Traveling waves are widely used for PD location, as introduced in 1960 by Kreuger [25]. This method

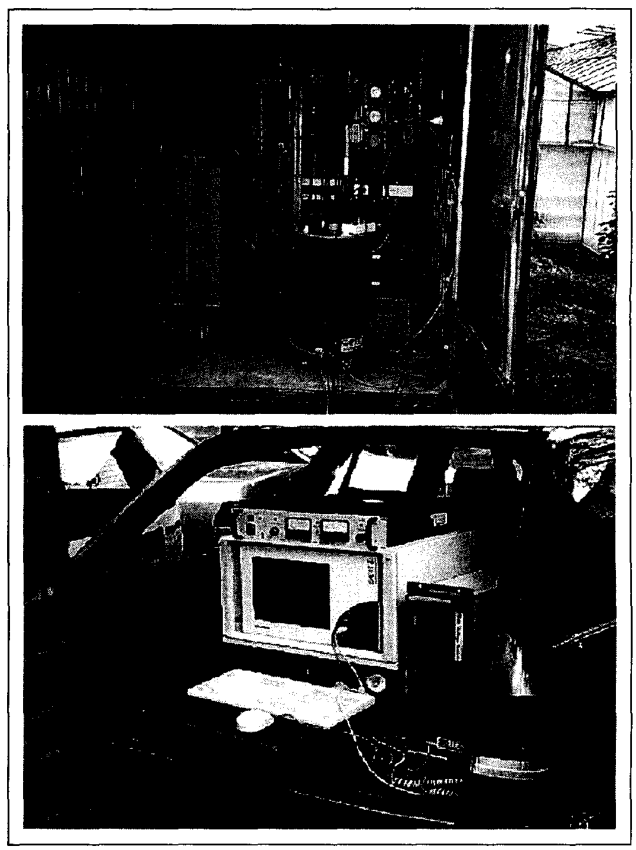


Fig. 14 On-site PD diagnosis of a 3 km long, 10 kV power cable using a 50 kV oscillating wave test system
Top: unit consisting of low loss air core, HV divider and PD coupling device connected to the cable termination,
Bottom: HV power supply, control and data acquisition unit

was automated a few years ago and is now widely used in shielded laboratories (see Fig. 14 and [26]).

If PD measurements on power cables have to be performed on site, different solutions are needed [27-31]. One proposed recently is based on nondestructive PD measurements using oscillating waves [32]. This method is used to energize, measure, and locate partial discharges in power cables on site, in accordance with IEC 60270 recommendations.

The oscillating wave test system consists of a digitally controlled flexible power supply to charge long cable lengths for resonant excitation at power frequencies of a few hundreds of Hz and a fast digital recording and statistical evaluation system for discharges (see Fig. 14). In this method, the cable sample is charged with a dc power supply over a period of just a few seconds to the usual service voltage. Then a specially designed solid state switch connects an air-core inductor to the cable sample in a closure time of <1 μs. Then the circuit oscillates through a series of voltage cycles at its resonant frequency: $f = 1/(2\pi \bullet \sqrt{L} \bullet C)$ where L represents the fixed inductance of the air core and C represents the capacitance of the cable sample. The air-core inductor has a low loss factor and is designed so that the resonant frequency lies in the range immediately above the power frequency of the service voltage: 50 Hz to 1 kHz.

Specifically, this compact, lightweight solution is used to generate HV oscillating waves with a duration of a few tens of cycles of ac voltage at frequencies up to a few hundreds of Hz. The analysis of PD in power cables using this technique represents a new advance in the adaptation of the latest digital technology for HV insulation diagnosis.

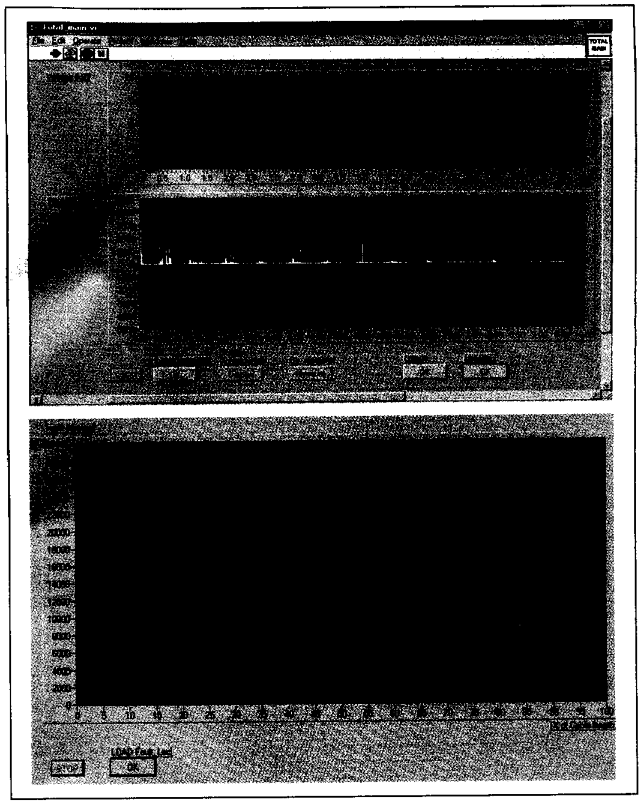


Fig. 15 On-site PD analysis of medium voltage power cables using the oscillating wave test method
Top: measurement display showing internal discharges after applying a 12 kV oscillating wave to a 12 kV XLPE power cable
Bottom: display of statistical evaluation obtained after three 12 kV oscillating waves applied to a 12 kV paper-oil cable; location of PD in a joint

Recognition of Defects in GIS

Acceptance tests and periodic off-line measurements of SF_6 gas-insulated test objects are restricted to the measurement of PD inception voltage (in kV) and maximum discharge magnitude in pC and comparing these with the test specifications. The test objects may be GIS substations or GIS components such as switchgear, disconnectors, and bus bars. If the permitted PD level is exceeded, then the main goal of evaluation in GIS is to localize the discharge source. For periodic inspection, it is also possible to use VHF/UHF sensors to measure PD signals on-line [33-34]. The VHF/UHF detection circuit usually consists of a sensor and a spectrum analyzer (see Fig. 16 and [35-36]).

The main objective of a PD measurement, whether it is based on IEC 60270 or VHF/UHF, is to assist with the recognition and location of the discharging defect. To support the evaluation process during a measurement it is possible to use reference PD patterns of typical defects. Some examples of typical GIS defects are described below.

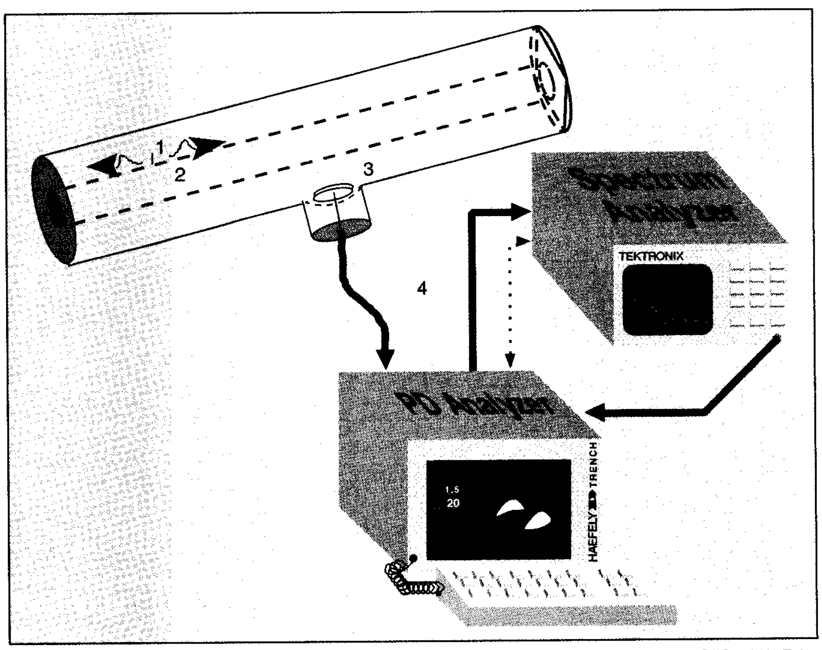


Fig. 16 Four important components to VHF/UHF PD measurements in GIS: (1) Discharging defect, (2) Excitation of traveling waves, (3) Transfer function sensor, (4) Data processing

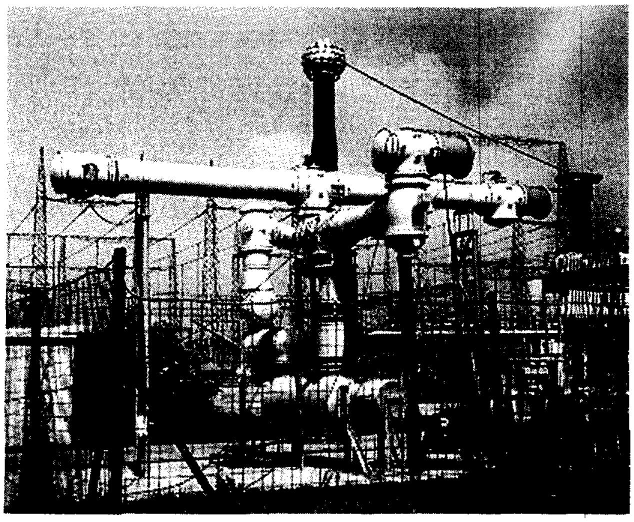


Fig. 17 420 kV GIS test setup

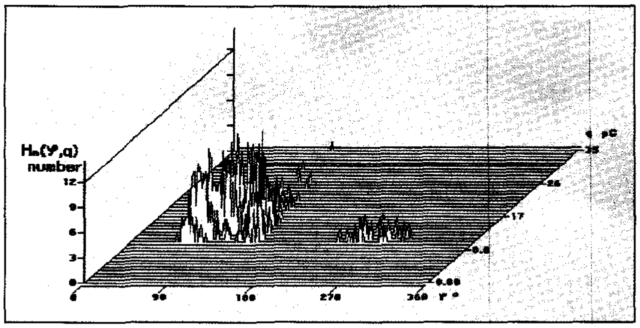


Fig. 18 Protrusion on the conductor at 220 kV

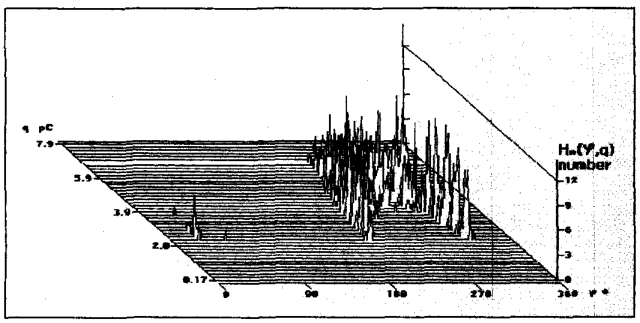


Fig. 19 Protrusion on the enclosure at 90 kV

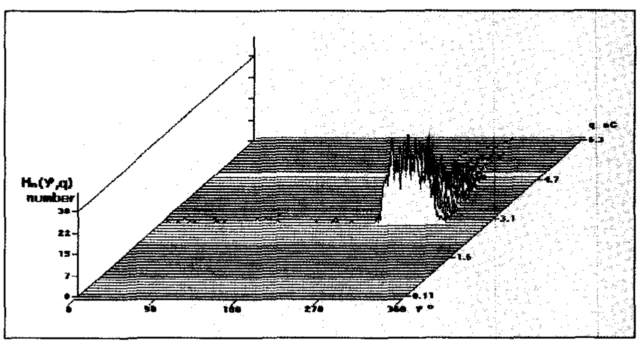


Fig. 20 Particle on insulator at 294 kV

Protrusion on the HV conductor represents sharp conducting particles that may occur on the HV electrode inside the GIS installation. Fig. 18 shows a typical phase-resolved plot.

Protrusion on the enclosure represents sharp conducting particles on the surface of the enclosure. Fig. 19 shows a phase-resolved plot. It follows from this comparison that the asymmetry between discharges in the positive and negative half of the applied ac voltage in case of a protrusion on the enclosure and a protrusion on the conductor is typical for both defects.

A particle on an insulator means a small conducting particle is contacting the surface of an insulator (spacer) and is distorting the field by producing a local field concentration. As a result, the breakdown voltage along the surface is diminished and in some cases discharges may occur before the breakdown occurs. Fig. 20 shows a phase-resolved plot.

A free-moving particle inside the enclosure means a conducting particle that is not fixed to any of the electrodes or insulators and may move (jump) inside the enclosure with a certain frequency. As a result, PD occurs, producing patterns as shown in Fig. 21. In contrast to the three defects mentioned above, a typical sinusoidal shape can be observed in the phase-resolved plot for this defect.

Internal defect in the moving parts: Circuit breakers and disconnectors are mechanically and electrically stressed during their service life. As a result, ageing processes occur inside the elements. An example of internal discharges in the grading capacitances of switchgear is shown in Fig. 23.

Foreign particles and ageing processes of solid materials are not the only contributors to GIS failures. Floating parts in the installation, i.e., electrodes imperfectly connected to HV potential, may cause regularly repeating discharge

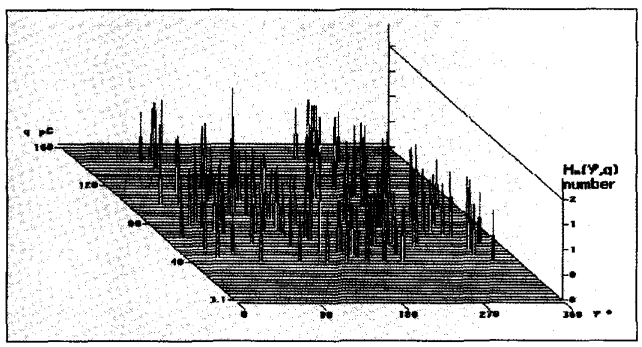


Fig. 21 Free-moving particle at 261 kV

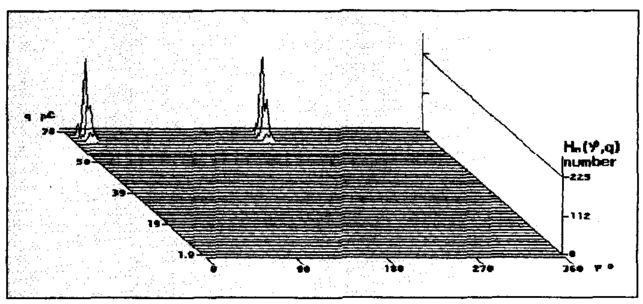


Fig. 22 Floating electrode in 4 bar SF_6

groups of the same amplitude (see Fig. 22). This pattern confirms the observation made before that each of the GIS defects is characterized by its own PD pattern. PD quantities processed by a digital PD analyzer [16-18] can provide further information for evaluation and diagnosis of PD measurements in GIS.

The systematic approach of examining digitally acquired PD quantities lays the foundation for a more systematic analysis of the different digital techniques and statistical tools that are in use in the field of recognition and diagnosis of discharges in GIS components.

Fig. 24 shows an example of statistical analysis using digital tools applied to four different PD fault patterns: a protrusion on the conductor, a protrusion on the enclosure, free-moving particles, and a particle fixed to an insulator. Recognition, discrimination, and classification of these faults are shown to be possible using digital tools.

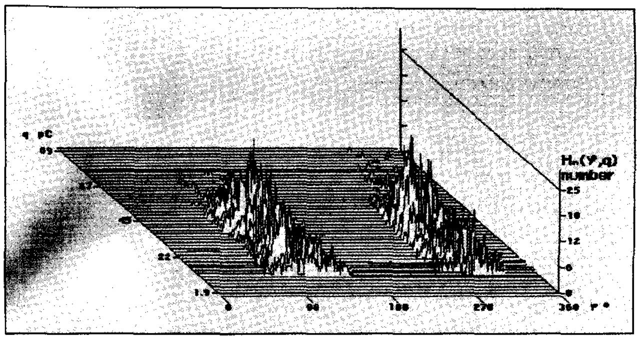


Fig. 23 Internal fault in switchgear at 138 kV

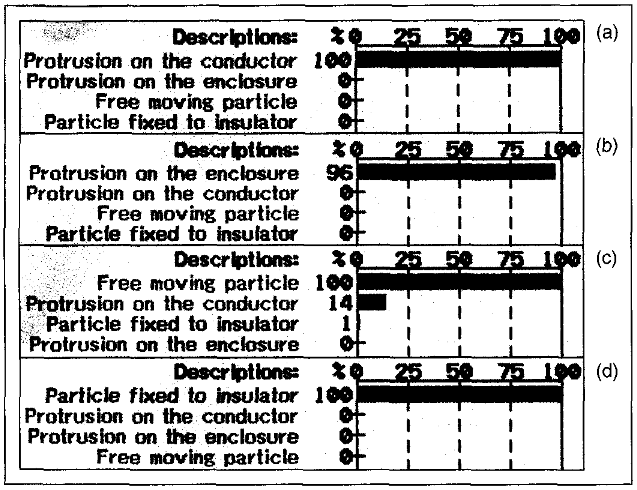


Fig. 24 Statistical analysis according to [12, 16-18] applied to four different PD patterns: (a) protrusion on the conductor, (b) protrusion on the enclosure, (c) free moving particle, (d) particle fixed to an insulator

PD Pattern Analysis of On-Line Measurements on Rotating Machines

In addition to periodic off-line PD testing, on-line PD measurement is an accepted method for rotating machines [23]. Using experience gained from off-line PD tests, this method can be utilized for condition-based monitoring of the stator insulation [37-40].

The PD signals are measured by a specially adapted digital PD detector (Figs. 25 and 26) using capacitive or inductive couplers while the generator is in regular operation. The couplers are permanently installed on the generator (at least one on each phase) and an on-line test can then be performed. This type of measurement is easily performed without interrupting the operation of the generator. As a result, the PD measurement is taken on a sample under operational thermal and mechanical stresses. Two difficulties arise when such PD measurements are needed:

- system interference may occur in the measuring circuit due to the power plant or from rotor excitation;
- complex propagation of PD signals through the stator winding occurs, resulting in cross-talk. This is due to the fact that all three phases are energized at the same time.

A spectrum analyzer (SA) can be used as a tuned filter to suppress external noise. The SA is tuned to a frequency in the range of 10 MHz - 100 MHz where PD from the stator insulation dominates the noise signals (see Fig. 27). This measurement method is known as the VHF PD detection technique due to the frequency range involved. The level of PD signals at the selected center frequency f_0 is demodulated to some hundreds of kHz and displayed on a 50 Hz time base. As a result, the measured signals can be further processed by a conventional PD analyzer with

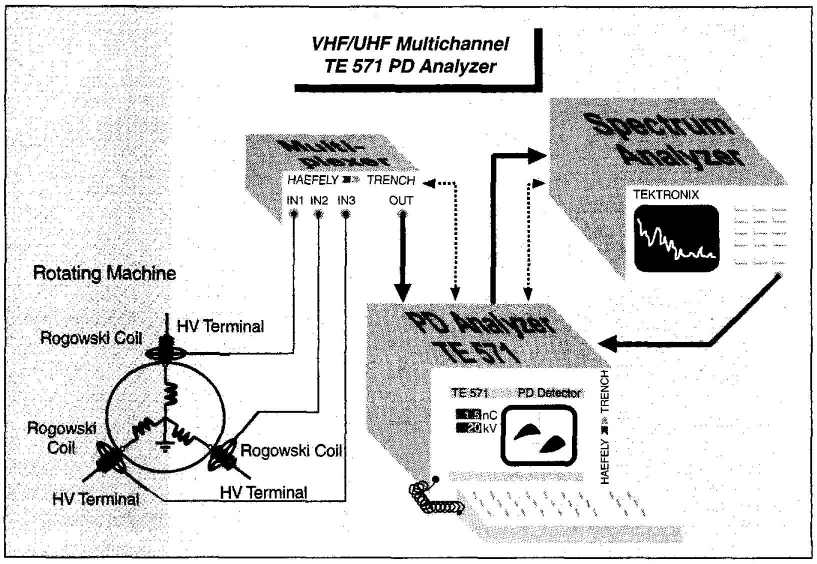


Fig. 25 Measuring setup used for VHF PD detection on rotating machines with a digital PD analyzer

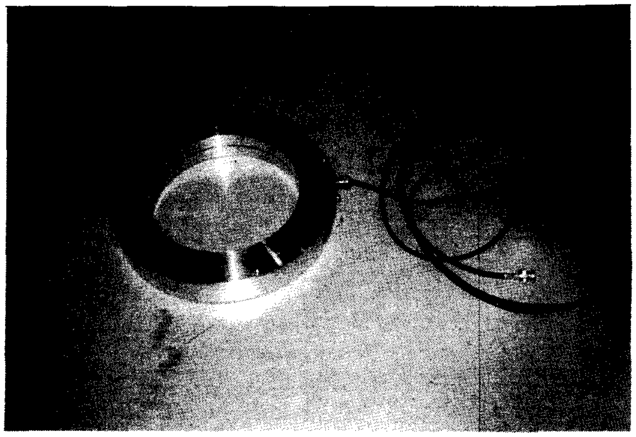


Fig. 26 VHF PD coupler for TE 571 PD analyzer (see Fig. 25): type: split ring Rogowski coil, 160 mm dia., terminating impedance: 50, bandwidth: 5-100 MHz, sensitivity: 96 mV/A

the goal of applying the broader experience of phase resolved PD pattern recognition [41-42].

Partial Discharge Patterns

As mentioned above, the measured PD patterns will reveal the single-phase PD response together with PD responses from the other phases due to the effect known as cross-talk. The position of the single-phase patterns with respect to the power cycle of phase U is illustrated in Fig. 28, showing the 120° shift between the phases.

The selection of a suitable resonant frequency for measurement is an exceptionally delicate procedure. This is illustrated in Fig. 29, which shows five PD patterns measured on the same phase of a generator at different resonant frequencies. At f_0 = 18 MHz the PD pattern is that of the measured phase. At f_0 = 30 MHz and f_0 = 62 MHz the PD pattern observed is that of the measured phase together with cross-talk. No response at all is measured at f_0 = 48 MHz and at f_0 = 64 MHz only cross-talk is measured.

The results of on-line measurements performed on a 155 MW and a 650 MW turbogenerator clearly illustrate this influence of the center frequency chosen on the following responses (see Fig. 30):

- the PD response of the measured phase, i.e., the PD activity originating from that phase;
- the cross-talk PD response, i.e., the PD activity originating from the other phases;
- the disturbance response, i.e., disturbances originating from the power plant and from the generator itself (e.g., rotor excitation).

Evaluation for Condition Monitoring

When a suitable frequency is found and selected for the measurement of the phase's own PD pattern, the pattern's characteristics can be used for identification of the insulation state. Experience resulting from analysis of off-line PD tests can be used to assist in the interpretation of PD patterns.

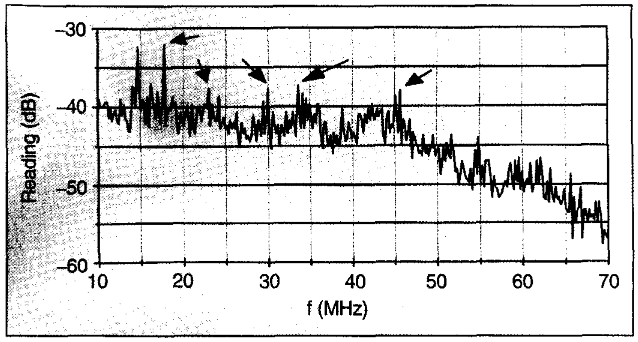


Fig. 27 Example of FS as obtained with the SA. The peaks at frequencies marked by the arrows indicate response above the noise level at these values of f_0.

For example, Fig. 30 shows the three-dimensional Hn(γ,q) distribution of a measurement on phase U of a 155 MW turbogenerator. The measurement was performed at f_0 = 53 MHz. The pattern shows the phase's own PD, PD cross-talk and disturbances. The phase's own PD pattern shows the characteristics of a regular PD pattern of insulation with no significant degradation [11].

Several conclusions can be drawn, based on experience gained from the on-line technique for PD tests presented above.

On-line VHF detection of PD processes in the insulation of a generator phase can be performed with a number of suitable SA center frequencies.

Careful selection of center frequencies can provide information about the insulation condition of the phases of a generator by analysis of the PD patterns. It can be expected that, in the course of time, local insulation degradation and disturbances will be identifiable by the PD pattern deviation.

Conclusions and Suggestions

It has been shown in practical cases that a digital PD system provides additional information, can support the documentation and analysis of a PD measurement, can help to

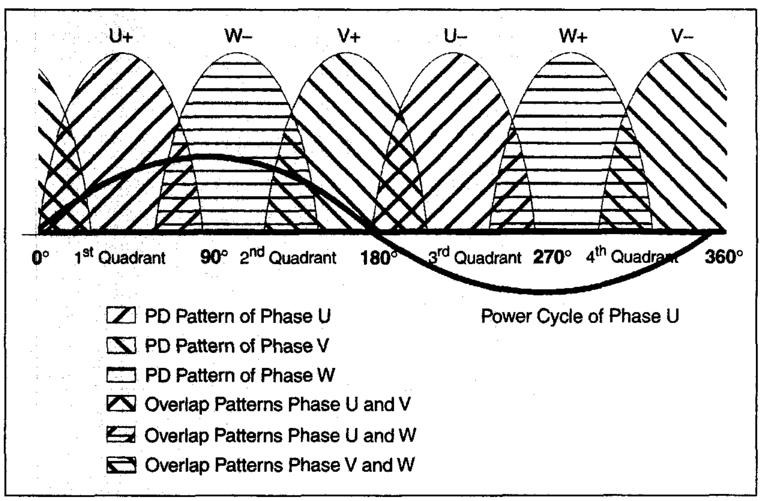


Fig. 28 Positions of the single-phase patterns with respect to the power cycle of phase U

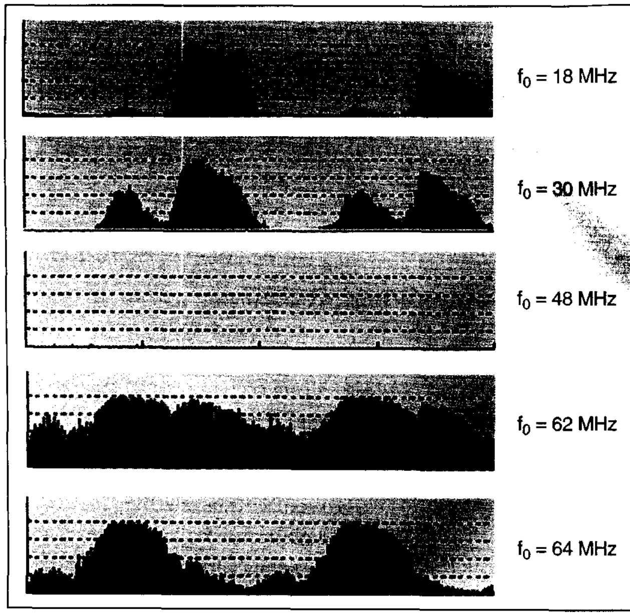


Fig. 29 Demonstration of the influence of f_0. Measurement at different f_0 on phase W of a 650 MW generator produces different patterns.

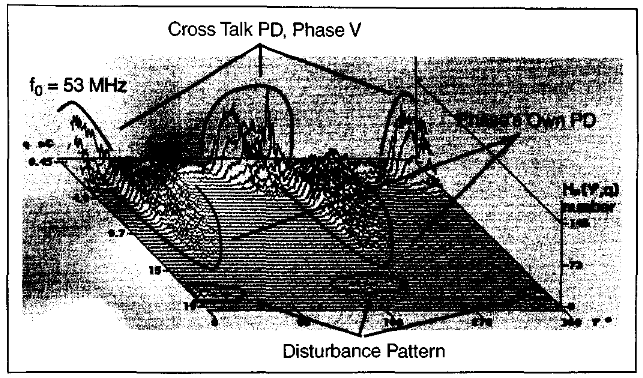


Fig. 30 $H_n(\varphi,q)$ distribution as measured on phase U of a 155 MW turbogenerator at f_0 = 53 MHz. The pattern shows a regular shape for phase-own PD patterns (no degradation), as well as cross-talk and disturbances.

inventory and evaluate different measurements, but is no 100% substitute for our experience. In particular the following have been shown:

A) Digital PD processing provides several quantities to evaluate discharges in HV equipment.

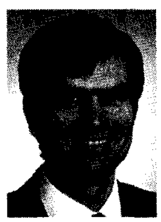
B) A PD database is an important tool for recognizing different defects and analyzing changes in the insulation.

C) The combination of PD quantities, database application and classification tools can be applied to PD diagnosis of power transformers, HV cables, generators and GIS.

The discussion of this paper could lay the foundation for a more systematic analysis of the different digital techniques and statistical tools that are in use in the field of recognition and diagnosis of discharges in HV components.

Edward Gulski was born in 1958 in Poland. In 1982 he received from Dresden University of Technology in Germany the M.S. degree in information technology. From 1982 until 1986 he worked as research assistant at the HV laboratory of Dresden University of Technology. In 1987 he joined the HV laboratory of the Delft University of Technology in The Netherlands where he performed research in the field of partial discharge diagnostic. In 1991 he received the Ph.D. degree from Delft University of Technology. At present he is associate professor at Delft University involved in education and research in the field of insulation diagnostics of HV components. He is a member of different CIGRE working groups and task forces.

Johan J. Smit was born in 1949 in The Netherlands. After receiving his master's degree in 1974 in experimental physics at the University of Amsterdam he received his Ph.D. at the State University of Leiden in 1979 for his research in magnetism on behalf of the National Science Foundation. Next he was employed for 17 years at KEMA in Arnhem, where he became section manager within the transmission and distribution company. Since 1996 he has been a professor in high voltage technology at the Delft University of Technology. Currently his specific areas of interest are dc and ac HV materials, advanced diagnostics, and maintenance support systems. He is a member of the Technical Committee of IEC 98 on Electrical Insulation Systems. In 1993 he became secretary of CIGRE Study Committee 15, Materials for Electrotechnology, of which he is now chairman.



Roger Brooks studied computer science at Northeastern University in Boston, Mass. And New York University and began working as an electronics engineer at Sensormatic Electronics in Florida in 1977, where his work ranged from low-frequency magnetics to microwave electronics. He was registered as a professional engineer in Washington, DC in 1984 on the basis of self-study, never having completed a degree program in engineering. He subsequently worked as a test engineer at DEC's disk drive division in Colorado Springs, 1984-87, and directed the engineering department at Boca Research from 1989 to 1992, when he moved to Switzerland with his wife, who is Swiss. In 1998 he was awarded senior membership in the IEEE. He recently left his post of four years as manager of engineering at Haefely Trench, Tettex Inst. Division, to lead the software development group at Loewenfels Partner in Lucerne.

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